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U.S. WAR DEPARTMENT

TECHNICAL MANUAL

**ELEMENTARY PHYSICS
FOR PILOT TRAINEES**

April 22, 1942



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WAR DEPARTMENT,
WASHINGTON, April 22, 1942.

ELEMENTARY PHYSICS FOR PILOT TRAINEES

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SECTION I

SCIENCE, PHYSICS, AND METEOROLOGY

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1. Definitions.—*a.* Science, in the generally accepted meaning of the term, is knowledge systematized and formulated with reference to the discovery of general truths or the operation of natural laws.

b. Physics is the science which treats of the laws and properties of matter and the forces acting upon it. It is the science of energy and rests upon the fundamental modern doctrine of the conservation of energy. Inasmuch as the majority of the laws of physics are expressible with some accuracy in terms of mathematical relationships, physics is said to be an exact science. At one time the great divisions

of science were kept well apart. Now we find such lines of inquiry as physical chemistry, astrophysics, biochemistry, physical optics, etc., filling the gaps between them so effectively that they run together and fade into one another like the colors of the spectrum.

c. Meteorology is sometimes considered as a branch of physics ("Physics of the Air") and in its broader sense includes a study of the laws of physics as applied to the atmosphere. Meteorology is a branch of natural science that treats of changing conditions in the atmosphere. It is the science of the atmosphere and its phenomena, those phenomena which collectively are called "the weather."

2. Importance of weather.—a. Because of their infinite variety and their intimate relation to all our activities, the phenomena of the weather are subjects of never ending interest. They are not only of interest but of great importance, since weather is one of the chief elements in man's life.

b. The importance of weather and weather forecasting to aviation is obvious. Aviators, who are especially at the mercy of the weather since flying schedules are maintained in all seasons, are asking meteorologists to forecast the weather conditions not only for points on the ground but for elevations far above the ground.

c. Weather has played an important part in wars throughout history. In modern warfare weather assumes even greater importance because of the use of airplanes, and because of the swift moves made over great distances by mobile units. Early campaigns by the German army apparently were timed to take advantage of weather conditions which had been accurately forecast. Knowledge of Atlantic weather conditions and the forecasting of weather over northwest Europe would have been facilitated had Germany succeeded in establishing weather stations in Greenland.

3. Purpose of weather course.—a. Weather courses for pilots are not given for the purpose of making them into accurate forecasters.

b. The aim of a weather course for aviators is to acquaint them with the terminology and fundamental principles of meteorology. This is necessary in order for pilots to be able to make adequate use of the weather information available. Pilots should be taught to interpret weather maps, weather reports, and weather forecasts; and should know how to make use of this information in flight. When weather information is either inadequate or in error, pilots should have sufficient understanding of weather principles to make correct decisions if trouble arises.

c. On any flight, it is necessary for pilots to have a reasonable idea of probable weather to be encountered, and it is also necessary for

them to have enough knowledge of weather to recognize unforeseen, hazardous conditions encountered en route, and make decisions which will bring about successful termination of the flight and not endanger themselves, their passengers, or their cargo.

d. The importance of weather to a pilot cannot be overemphasized. A large percentage of all aircraft accidents are attributable to ignorance concerning weather.

4. Reason for weather course.—*a.* Experience has shown that the fundamentals of meteorology cannot be grasped without first preparing the student for the subject. Weather for pilots cannot be set down as a simple set of rules that anybody can memorize. It is absolutely essential that some of the fundamental theory of weather be known and understood.

b. Rules are good things to have alongside a knowledge of the fundamental theory. By themselves, however, they are not sufficient. Rules are easily forgotten, and a pilot who depends on them may find death just around the corner. If he forgets his rules when tough going is encountered in flights, he will not be able to figure out what to do. If, on the other hand, a pilot knows the fundamental theory of meteorology, he will be able to determine which way to turn and what to do when flying through bad weather. That is, the situation may be correctly analyzed by the pilot, and he should not have to depend on memory, which is forever a human failing.

c. Since the theory of meteorology needs to be understood and since 75 percent of all would-be pilots lack the proper background for an understanding of this theory, a course to supply this background is necessary. Thus the principal aim of this course is a preparation for studies in meteorology. Since the importance of meteorology cannot be overemphasized, it follows that this course in physics will be fundamental to skillful and safe piloting.

QUESTIONS

1. Define science; physics; meteorology.
2. Why is this course in "Physics of Weather" essential to a student pilot?
3. Give essential differences between flying in wartime and peacetime.

SECTION II

ATMOSPHERE

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5. General.—The atmosphere is the laboratory in which the meteorologist carries on his experiments. This vast laboratory is unique among scientific laboratories in that the experimenter has practically no control over the reactions that take place within it. While the chemist, the physicist, the biologist, and even the geologist may more or less control the conditions of the problem that he is investigating, the meteorologist can do little more than to observe and to ponder. His experimental problems are very difficult because the elements with which he has to deal are constantly changing. It will be the purpose of this section to point out some of the more interesting features of this ocean of air in the lowermost depths of which man walks and flies.

6. Definition.—The word atmosphere is derived from the Greek words “atmos,” which means vapor, and “sphaira,” which means sphere. It is, therefore, the spherical gaseous layer which envelops the earth, the fluid sea at the bottom of which we live.

7. Composition.—*a.* The air, or the material of which the atmosphere is composed, is a mechanical mixture of a number of different gases.

b. That air is a mixture and not a compound is evident from the following facts:

(1) The relative weights of the components are not in proportion to their atomic weights.

(2) The relative portions of the components vary somewhat (they are not constant).

(3) The components can be separated by physical methods. For example, if pure dry air is cooled, oxygen condenses (liquefies) before nitrogen, since it has a higher boiling point; whereas if air were a compound, there would not be a separation of the constituents of the air by separate liquefaction. Likewise, when liquid air evaporates, the nitrogen evaporates first because it has a lower boiling point, leaving almost pure oxygen. If air were a compound, there would be no

separate evaporation, since there would be just one substance to evaporate.

c. A sample of dry and pure air contains about 78 percent (by volume) nitrogen (N_2), 21 percent oxygen (O_2), almost 1 percent argon (A), and about 0.03 percent carbon dioxide (CO_2). Together these four gases constitute about 99.99 percent of dry and pure air. The remaining 0.01 percent represents traces of hydrogen and several rare gases such as neon, krypton, helium, and xenon. The average of the proportions of the gases in dry air is shown in table I.

TABLE I.—*Constituents of air*

	Density ¹	Percent by volume	Percent by weight
Air.....	1. 2929	100. 00	100. 00
Nitrogen.....	1. 2506	78. 03	75. 48
Oxygen.....	1. 4290	20. 99	23. 18
Argon.....	1. 7837	. 94	1. 29
Carbon dioxide.....	1. 9769	. 03	. 45
Hydrogen.....	. 0899	. 01	. 0007
Neon.....	. 9004	. 0012	. 0008
Helium.....	. 1785	. 0004	3×10^{-5}
Krypton.....	3. 708	5×10^{-6}	$1. 5 \times 10^{-5}$
Xenon.....	5. 851	5×10^{-7}	2×10^{-6}

¹ Density is given in grams per liter at 0° C. and 76 cm. mercury (Hg).

d. The air also contains a variable amount of water vapor and dust particles. In many respects, the water vapor is the most important constituent of the atmosphere in spite of the fact that the weight of the water vapor never exceeds 4 percent of the total weight of the atmosphere. Its importance to agriculture is obvious, yet it is also responsible for adverse flying conditions—the three most dangerous flying hazards being fog, thunderstorms, and icing.

e. The maximum amount of water vapor that the air can absorb depends entirely upon the temperature of the air; the higher the temperature of the air, the more water vapor it can hold. The air is said to be saturated with moisture when this maximum amount is reached.

f. Dust and other minute particles also exist in the atmosphere in variable amounts. When there is a high concentration of these particles (impurities) in the atmosphere, we observe what is known as *haze*. This phenomenon is a definite flying hazard because it results in lowering of visibility.

g. The main sources of these impurities are arid regions, seas, industrial regions, forest fires, and volcanoes.

h. Arid regions such as deserts and very dry country as in Kansas and Oklahoma are prominent sources of dust particles. Minute grains of dust are picked up and whirled by the winds, which readily distribute them throughout the lower atmosphere, sometimes far from the source. Strong winds may give rise to sand and dust storms of such intensity as to make flying extremely hazardous.

i. Observations show that the air normally contains a considerable amount of salts. Spray is whirled up from the ocean through the action of the winds, and when it evaporates, the salt remains in the air in the form of minute particles.

j. Combustion contributes a considerable quantity of impurities to the atmosphere. The smoke from cities, forest fires, and volcanoes contains many very fine particles. The smoke from a fire may seem to clear up and disappear at a small distance from its source, but this simply means that the myriads of particles have lost their shape as a group and are scattered. Being extremely fine, they stay in the air for a long time.

k. Such dust and salt particles as have been discussed are inorganic. A small part of the vast amount of dust in the atmosphere is of organic origin.

l. Pollen from flowering plants and plant spores is a good example of organic dust in the air. Being so small, it is picked up by the air and often blown hundreds of miles. Hay fever has been attributed to the pollen of ragweeds and other plants.

m. Other examples of organic dust in the air are the various kinds of minute living creatures such as bacteria and yeast cells. The germs causing many of man's most dreaded diseases are sometimes carried by the air.

n. The presence of dust in the atmosphere is important for other reasons besides its influence on visibility. If the air were perfectly pure, there could be no appreciable condensation of water vapor. When the air is cooled to its saturation temperature, condensation takes place on certain active (hygroscopic) nuclei. Salt particles from the ocean and various products of combustion are most active as condensation nuclei, observations showing that such particles are present in the atmosphere in abundant amounts.

o. Dust particles scatter light and help to give the sky its characteristic blue appearance. They also help to color sunsets by acting as a light filter, removing the blue and leaving the red transmitted light. Scattered light also promotes twilight after the sun has set.

p. Dust absorbs some of the sun's heat, and any great increase in the dust content of the air is likely to be accompanied by a decrease in insolation (solar radiation received by the earth's surface).

8. Density of atmosphere.—*a.* We live at the bottom of a deep sea composed of a mixture of many gases that make up a very highly compressible fluid, the air. This fluid has a mass similar to any other substance and is therefore subject to the forces of gravity. The gravitational force, owing to the mass of the earth, pulls the air toward it and thus holds the earth's atmosphere.

b. Since this fluid, the atmosphere, is compressible, those layers or parts at the bottom are compressed considerably more than the upper layers that are not supporting so great a weight of air above them.

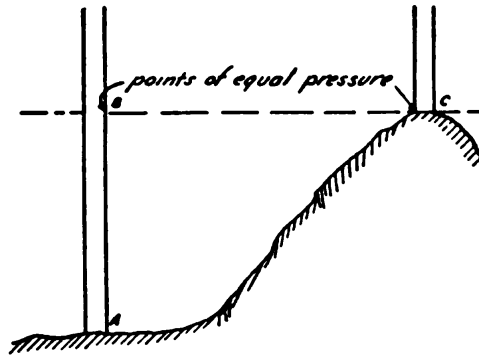


FIGURE 1.—Decrease of pressure with altitude.

Thus the density of the air close to the surface will be greater than the density of air at a higher elevation.

c. Density is defined as mass per unit volume ($\frac{\text{mass}}{\text{volume}}$). Thus the density of the atmosphere may be measured and expressed either in terms of grams per cubic centimeter or in pounds per cubic foot.

d. At ordinary pressure and temperature, the weight of a sample of air near the earth's surface is about $\frac{1}{800}$ of the weight of an equal volume of water. Thus it has been found that 1 cubic foot of air weighs about 0.075 pound and that 1 cubic centimeter of air weighs about 13×10^{-4} grams (0.0013 gram) near the earth's surface. Thus, the density of air near the earth's surface is about 0.075 pound per cubic foot and 13×10^{-4} grams per cubic centimeter.

e. It might be of interest to note and compare the molecular weights of air and water. That of air is 28.735, whereas water has a molecular weight of 18.00.

f. In consequence of this weight, the atmosphere exerts a certain pressure upon the earth's surface. The physicist defines pressure as the force distributed over a unit area in terms of pounds per square inch, grams per square centimeter, and so on. In any fluid, the pressure on the bottom is equal to the weight of the fluid above the surface divided by the area of the surface.

g. At the earth's surface, the atmosphere exerts a pressure amounting to about 14.7 pounds per square inch. This means that, under normal conditions, a column of air 1 inch square reaching from the earth's surface to the upper limits of the atmosphere will weigh 14.7 pounds. This is equivalent in weight to a column of water 34 feet high, or to a column of mercury 29.92 inches (76 centimeters) high. Since water barometers would be too big to measure atmospheric pressure, mercurial barometers are used.

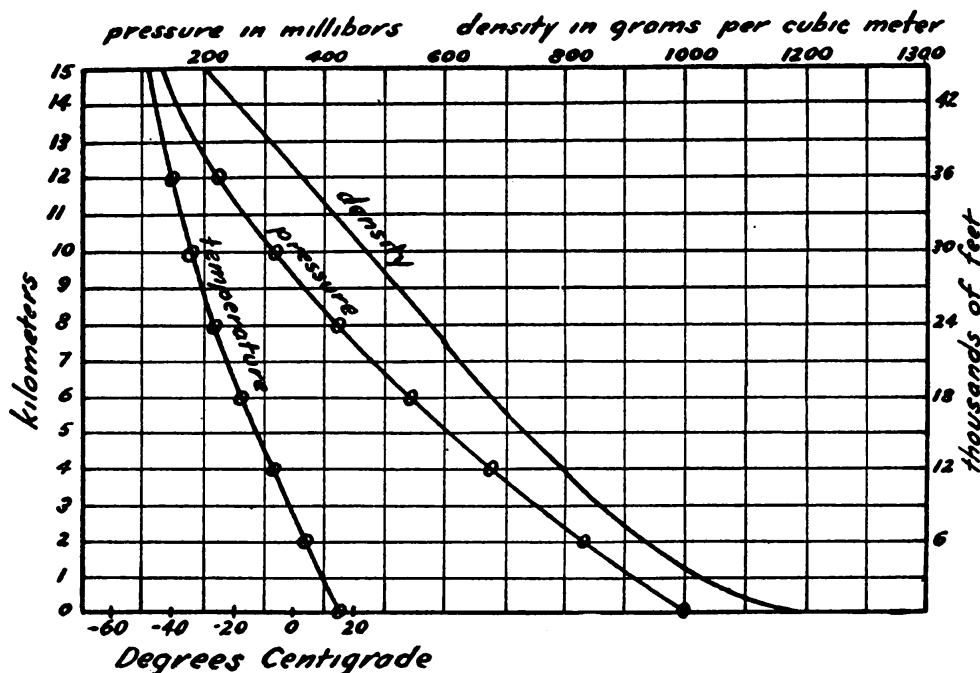


FIGURE 2.—Normal variation of temperature, pressure, and density with altitude in atmosphere (middle latitudes in winter).

h. The column of air above a surface becomes shorter as we go up in the air. Therefore, there is a pressure decrease with an increase in altitude.

i. Pressures at *B* and *C* are equal. Pressure at *A* is greater than pressure at *B* by the weight of the column of air *AB*.

$$P = DGH$$

P = pressure

D = density

G = force of gravity

H = height

j. It is quite obvious now that pressure decreases as altitude increases. Since by equation, density is shown to be directly proportional to pressure, it should also be obvious that the density of air also decreases as altitude increases.

9. Height of atmosphere.—*a.* It is hard to visualize the upper atmosphere. Since the density of the air decreases with increase in altitude, we naturally think of the air as becoming thinner and thinner with increased elevation until it merges with whatever traces of gases there may be in interplanetary space. It is quite certain that the atmosphere could not extend upward for more than about 20,000 miles and still turn with the earth as it rotates on its axis. At this distance the centrifugal force due to the earth's rotation approaches the magnitude of gravity, and the earth could not retain the air.

b. Even though the atmosphere extends to great altitudes, it is only the lower part which is of importance to weather phenomena. The highest clouds (cirrus) are seldom more than 35,000 feet above the earth's surface, while 50 percent of the total weight and 90 percent of the total moisture content of the atmosphere are within 18,000 feet of the surface.

c. Although it is conceivable that the atmosphere may extend upward about 20,000 miles, little is known of that part above 150 miles (about 800,000 feet). Below 150 miles, however, scientists have been able to find out enough about the atmosphere to divide it into various well-defined layers.

10. Stratification of atmosphere.—*a.* It will be seen from figure 2 that the air temperature normally decreases with elevation up to about 36,000 feet and then remains more or less constant. The rate of decrease in temperature along the vertical is called the *lapse rate*. The lower part of the atmosphere, which normally is characterized by a relatively large lapse rate (rate of temperature decrease with altitude being greater in this part), is called the *troposphere*. The upper part of the atmosphere, which is characterized by an almost constant temperature along the vertical, is called the *stratosphere*. The transitional layer separating the stratosphere from the troposphere is called the *tropopause*. The height of the tropopause above the earth's surface varies considerably with latitude and season. Figure 3 shows the normal height of the tropopause and the mean distribution of temperature in the lower atmosphere. It is interesting to note that on the whole the temperature of the stratosphere decreases from the North Pole to the Equator.

b. Observations in the lower atmosphere are made by an instrument called a radio meteorograph or radio-sonde. It is a very light and small instrument consisting of pressure, temperature, and humidity measuring instruments rolled into one. The instrument includes a minute radio sender which transmits to the ground radio signals

indicating the values of pressure, temperature, and humidity. These instruments are carried by balloons which normally attain altitudes of 40,000 feet before they burst. Occasionally such balloons have reached altitudes exceeding 100,000 feet. From these observations and from recent studies of radiation, meteors, aurora borealis, the propagation of sound and radio waves, etc., it is possible to draw conclusions as to the structure of the upper atmosphere. Present knowledge of the stratification of the atmosphere may be summarized briefly as follows:

(1) In the troposphere the temperature normally decreases with altitude at a rate of approximately 2.0°C . per thousand feet. The

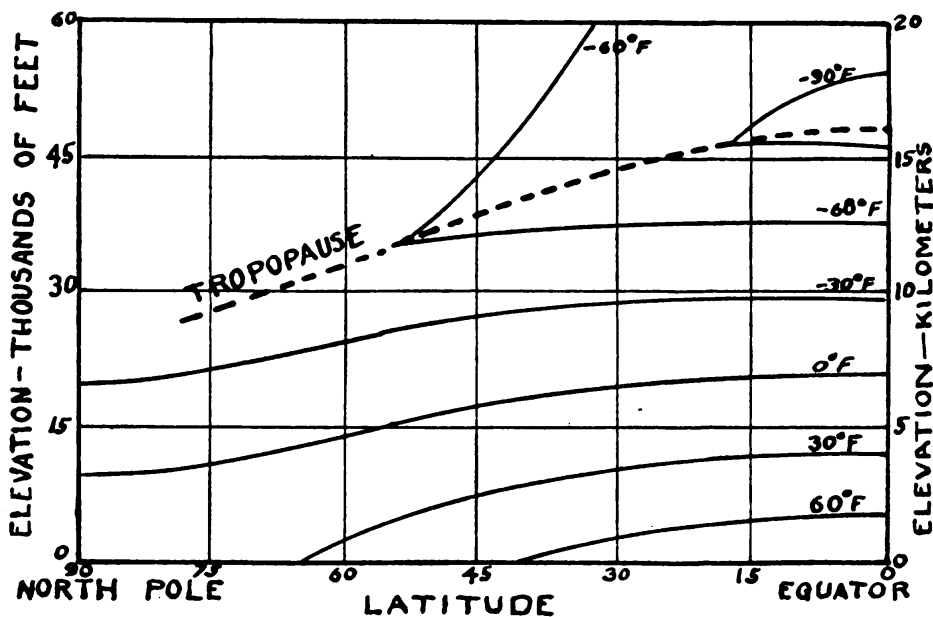


FIGURE 3.—Mean annual temperature in troposphere and lower stratosphere. (Note that stratosphere is warmer at Pole than at Equator.)

troposphere is relatively unstable; vertical currents occur frequently, leading to condensation, the formation of clouds, and precipitation. All ordinary weather phenomena develop within the troposphere, particularly in its lower half.

(2) At the tropopause the temperature stops decreasing with altitude (see fig. 2). From this level, the temperature remains constant or increases along the vertical as far as meteorograph instruments have reached.

(3) Above the tropopause lies a layer particularly rich in ozone (see fig. 4). Ozone is an allotropic form of oxygen having 3 atoms in its molecule (O_3) instead of the usual 2 (O_2). The ozone absorbs from 5 to 7 percent of the total incoming solar energy but radiates only a small amount, which in part at least may account for the higher temperature

encountered in the upper atmosphere. Although the stratosphere is usually cloudless, a special type of cloud (mother-of-pearl) is occasionally observed within the ozone layer. The space between the tropopause and ozone layer (see fig. 4) is always cloudless and in addition there are no vertical currents (rough air) here; therefore the lower stratosphere offers the nearest approach to ideal flying conditions.

(4) Statistical investigations show that meteors disappear most frequently either at about 260,000 feet (80 km.), or at about 130,000 feet (40 km.) above the earth's surface. This fact as well as the results of the propagation of sound waves seems to indicate that there is a layer of air between 130,000 and 260,000 feet which is extremely warm, perhaps 120° to 130° F. (60° to 70° C.).

(5) At about 200,000 feet (60 km.), there is a layer that tends to absorb radio waves. This layer is created through the action of the sun's rays; and, as a result, the range of radio stations, particularly that of short-wave stations, is greater by night than by day.

(6) Above the level of about 260,000 feet (80 km.) is the so-called *ionosphere*. The ionosphere derives its name from the increase in number of free ions existing within it. In the lower portion of it are the extremely rare noctilucent clouds. The ionosphere is also characterized by several electrically conducting layers of which the Kennelly-Heaviside layer (E layer) is the most important. This layer reflects radio waves back to the earth's surface and thus accounts for the long range of radio stations.

(7) The Aurora Borealis and kindred phenomena are most frequently observed within the lower part of the ionosphere. Recent measurements by Stormer have shown that auroras may occur even as high as 4,000,000 feet (about 758 miles or 1,220 kilometers) above the earth's surface. This shows that atmospheric matter is present in measurable amounts at great altitudes.

11. Function of atmosphere.—*a.* Perhaps the most important function of the atmosphere lies in the dependence of animal and plant life upon air. Without oxygen there could be no animal life and without carbon dioxide plants could not exist.

b. The atmosphere, however, serves many purposes other than sustaining animal and plant life.

(1) It serves as a blanket; that is, it keeps some of the ultraviolet radiation out, and yet keeps heat in. Air is a very poor conductor of heat, conducting it only about one-third as well as asbestos. It thus makes a good heat-insulating material, especially if it is not allowed to circulate. It is very transparent to the sun's radiation, and consequently is warmed but little by sunlight passing through it. Rather,

most of its heat is received from contact with the warm earth and by absorption of the long-wave radiation of the earth (particularly by the water vapor in the atmosphere).

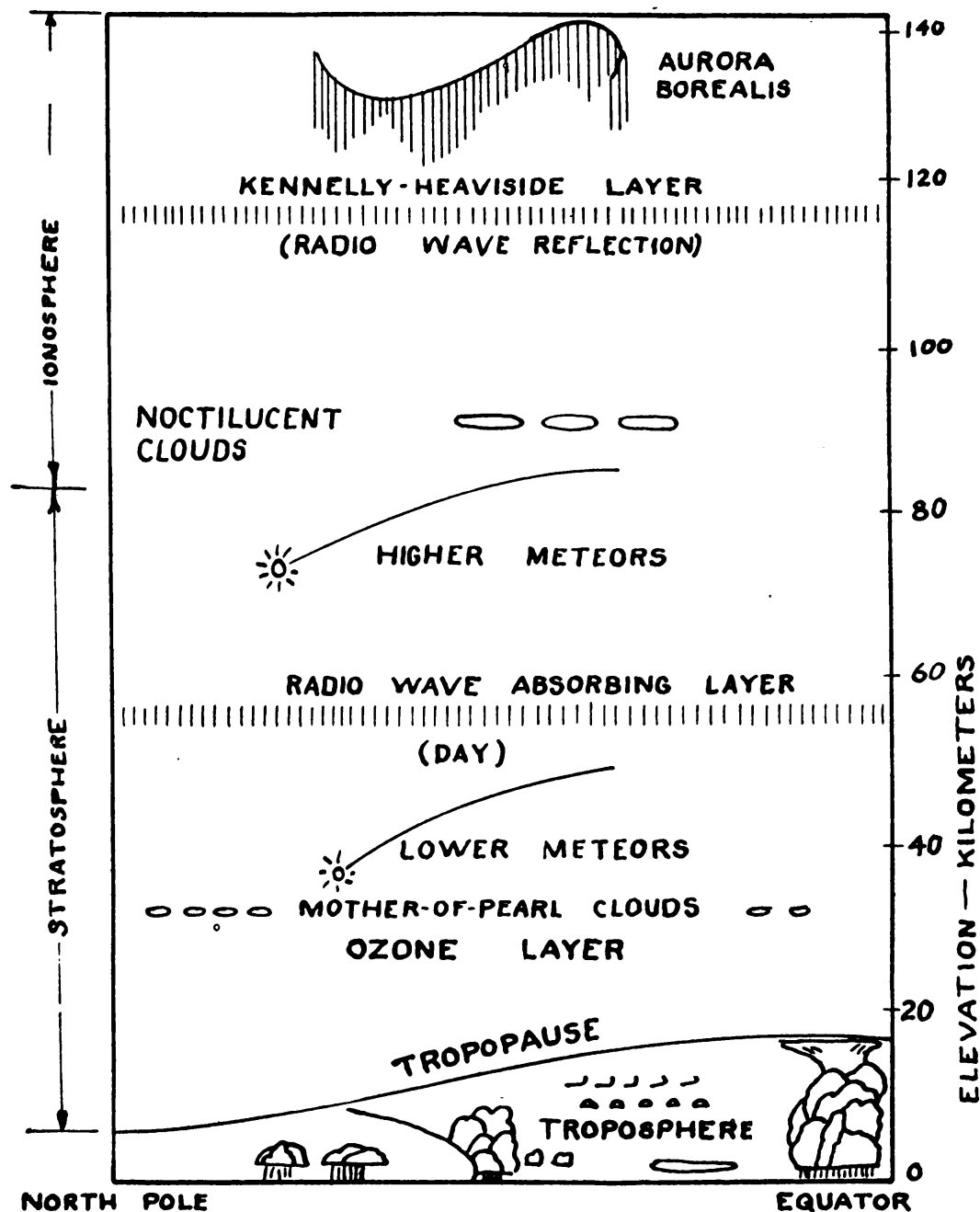


FIGURE 4.—Structure of atmosphere.

(2) Circulation in the atmosphere serves to transport moisture from lakes and oceans to land areas and precipitation of this moisture makes for good farm lands. Circulation likewise transports seeds, causing a widespread plant growth over large areas.

(3) Differential heating over the earth's surface causes energy contrasts in the atmosphere which result in movement of air, or winds. Efforts of the atmosphere to supply movement of air in an attempt to erase these energy contrasts and bring about equilibrium give rise to inclement weather.

(4) The atmosphere also functions as a medium of travel. It sustains the flight of birds and airplanes.

QUESTIONS

1. What is the atmosphere?
2. What evidence is there that the atmosphere is a mixture of gases and not a compound?
3. What four gases constitute about 99.99 percent of dry and pure air and what are their relative amounts?
4. What are the two important variables that exist in the atmosphere?
5. What is haze and why is it a flying hazard?
6. What are the main sources of dust particles in the atmosphere?
7. Why is it that salt particles are found in the atmosphere?
8. What relationship in the atmosphere exists between water vapor and dust particles?
9. What are two other functions of dust particles in the atmosphere?
10. Define pressure.
11. What causes atmospheric pressure?
12. At the earth's surface, what is the atmospheric pressure under normal conditions? Give your answer in three different units of measure.
13. Define density, and give values for the density of air near the earth's surface.
14. How do density and pressure vary with an increase in elevation?
15. What is the theoretical upper limit of the atmosphere? Explain.
16. Up to about what altitude is the weather important as far as flying is concerned?
17. How does the temperature vary with elevation in the troposphere? In the stratosphere?
18. How are upper air observations made?
19. Observations and measurements of the Aurora Borealis have shown that atmospheric matter in measurable amounts may be found as high as what altitude?
20. What is the most important function of the atmosphere? What two constituents of the atmosphere are concerned with this vital function?
21. Name four other functions of the atmosphere.

SECTION III

UNITS OF MEASURE

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12. General.—It has already been said that the facts and laws of physics may frequently be expressed in mathematical language. Physics is not merely descriptive. One cannot pursue it far without recognizing the existence of numerous quantitative relationships that require expression. Not only does one wish to know *what happens* under given conditions, but to what degree effects are produced by causes of given amount.

13. Magnitudes (fundamental and derived).—*a.* A magnitude is anything that may be considered as being greater or less in amount, degree, or extent. Thus, the height of a tower and the brightness of a lamp are magnitudes. Many kinds of magnitude are involved in the different branches of physics. Some of those most familiar are length, time, speed, weight, power, temperature, strength of an electric current, etc. One's ideas of some of these are so deep-seated and elemental that it is unnecessary or impossible to define them. This is true, for example, of length (meaning simply distance) and of time.

b. So far as the layman's understanding of them is concerned, these magnitudes are independent of each other and of everything else. Of many other familiar magnitudes, this is not true. To illustrate: speed cannot be thought of without connecting it with both length and time. It is distance per unit of time; that is, length and time must be combined in a definite way in order to express the idea of speed.

c. Just as in chemistry we recognize certain primary substances, called elements, out of which other substances are formed, so also in physics there are a small number of fundamental or elementary magnitudes, in terms of which most of the other magnitudes (consequently called secondary or derived magnitudes) can be expressed. Physicists are accustomed to regard the three magnitudes, length, time, and mass, as fundamental. All the other magnitudes, such as speed, are derived.

14. Idea of units and need for standards of weights and measures.—*a.* Before the fundamental and derived units are discussed, the idea of units and the need for standards should be made

clear. Perhaps they can be best explained by taking the fundamental unit of length and tracing some of its history.

b. Undoubtedly, the measurement of length must have come about through necessity. It is quite probable that pieces of string may have been used to produce desired lengths. For example, somebody may have used pieces of string to represent the length and width of a proposed hut. The timber was then cut to size by using these pieces of string to measure off the desired lengths.

c. However, each piece of string would measure only one thing. One string could measure the length of the hut but did not take into account its width. It is easily understood how extraordinarily difficult and troublesome this process might have been when many such measurements were to be made and recorded; still more so when others had to be informed about them. In addition, one can imagine how difficult it would have been to estimate long distances by such a process.

d. An enormous advance in the science of measurement was made when it was recognized that a long length could be defined by means of a unit and a number, which indicated how many times the unit must be placed end to end in a straight line in order to attain the desired longer length. It is possible that somebody in building a hut discovered that the length or width of the hut could be determined by the number of strides it would take to walk from one corner to another. The length of one stride was, therefore, chosen as the unit of length. Later this rather indefinite length of a stride was replaced by that of the foot, a more clearly defined unit, and still later, a stick was chosen as the standard foot which was to be the basis of all measurements of length.

e. It is not surprising that the first units were connected in some way with human beings—the stride, foot, the fathom equaling the distance which can be encompassed when the arms are outstretched, and the acre equaling the area of land which could be ploughed in a day. Each individual industry chose these primary units without concerning itself with another. Thus, until 1875, there were in existence the Prussian, Rhineland, English, and French foot. Even in the same country different units were used for different purposes. The mariner used knots and fathoms, the surveyor rods, the weaver ells, while the carpenter worked with feet and inches.

f. This variety of independent units was bound to cause inconveniences, especially when the introduction of the railway, steamship, telegraph, and telephone caused people of different countries to exchange their material as well as their intellectual goods with one

another. The need for having an absolutely permanent basis for weights and measures and the desirability of harmonizing the chaos which existed in this matter throughout the world resulted in the establishment of the metric system by the French Government in 1793. It has since been adopted by nearly every civilized country, although in Great Britain and the United States the familiar English system is still in use with the exception of scientific work, where the metric system prevails.

g. The English system is used more from habit than because of any real advantage it possesses. The metric system, arranged decimally like our system of money, is admirably adapted to every practical and scientific purpose. Thus millimeters, centimeters, kilometers, etc., are expressible in terms of the meter by simply moving the decimal point. Units of mass have a similar arrangement and notation.

h. With all this in mind, a discussion of both the fundamental and derived units in both the English and metric systems is in order.

15. Fundamental units.—The fundamental units are length, mass, and time. An absolute unit is one from which all like units may be derived. For example, the centimeter is considered the absolute unit of length in the French system and from it one can obtain other units of length such as the millimeter and kilometer. Thus it is evident why the metric system is often called the centimeter-gram-second (C. G. S.) system of absolute units, inasmuch as the centimeter, gram, and second are taken as the units of length, mass, and time, respectively. For the same reason, the English system is often called the foot-pound-second (F. P. S.) system.

a. Unit of length (L).—(1) The unit of length in the metric or C. G. S. system is the centimeter, or one-hundredth part of a meter. The meter conforms to the distance between ends of a bar of platinum which is kept in Paris, the bar being measured when it is the temperature of melting ice. This bar as a standard of length was established by the French Government in 1799 with a view to its becoming universal. It was intended to be exactly 1 ten-millionth of the distance from the equator to the pole measured along a meridian of the earth.

(2) The English standard of length, from which the foot and inch are determined, is the standard yard. This is the "distance between the centers of the transverse lines in the two gold plugs in the bronze bar deposited in the office of the Exchequer," measured at a temperature of 62° F.

(3) That there is rhyme and reason to the C. G. S. system may be seen from the following table of conversions:

$$1 \text{ millimeter (mm)} = \frac{1}{1000} \text{ meter (m).}$$

$$1 \text{ centimeter (cm)} = \frac{1}{100} \text{ meter.}$$

$$1 \text{ decimeter (dm)} = \frac{1}{10} \text{ meter.}$$

$$1 \text{ kilometer (km)} = 1,000 \text{ meters.}$$

or:

$$1,000 \text{ mm} = 100 \text{ cm} = 10 \text{ dm} = 1 \text{ m} = 0.001 \text{ km.}$$

(4) That there is no rhyme or reason to the English system other than force of habit is apparent from the following table:

$$36 \text{ inches (in.)} = 1 \text{ yard (yd.).}$$

$$3 \text{ feet (ft.)} = 1 \text{ yard.}$$

$$1 \text{ mile (mi.)} = 1,760 \text{ yards.}$$

Other equivalents in the English system are—

$$1 \text{ foot} = 12 \text{ inches.}$$

$$1 \text{ mile} = 5,280 \text{ feet.}$$

(5) A comparison between the two systems gives—

$$1 \text{ yard} = 91.44 \text{ centimeters.}$$

$$1 \text{ foot} = 30.48 \text{ centimeters.}$$

$$1 \text{ inch} = 2.54 \text{ centimeters.}$$

$$1 \text{ mile} = 1.60 \text{ kilometers.}$$

$$1 \text{ meter} = 39.37 \text{ inches.}$$

(6) Before the other fundamental units are discussed, it might be best to explain surface and volume, since both are measured in terms of length.

(7) A surface is defined as having length and breadth but no thickness. Thus, the floor of a house whose dimensions are 20 feet by 20 feet has 400 square feet (ft.²) of surface and the unit of surface is 1 square foot in the English system. In the C. G. S. system the unit of surface is 1 square centimeter (cm²).

(8) Volume is defined as the amount of space included by the surfaces of a solid. Thus the volume of a room having width, breadth, and height of 20 feet has a volume of 20 x 20 x 20 or 8,000 cubic feet (ft.³), the unit of volume in the English system being 1 cubic foot. One cubic centimeter (cc or cm³) is the unit of volume in the C. G. S. system.

(9) Volume is also defined as capacity or the ability to hold. Thus, there are measurements such as liter, quart, etc.:

1 liter (l) = 1,000 cc.

1 quart (qt.) = 1.057 liters.

1 quart = $57\frac{1}{4}$ cubic inches.

b. Unit of mass (M).—(1) The unit of mass in the C. G. S. system is the gram, one-thousandth part of the standard kilogram. The standard kilogram, which is a mass of platinum kept at Paris, was intended to represent the exact mass of a cubic decimeter of distilled water at its greatest density or at the temperature of 4° C.

(2) Since two masses may be compared with a far higher degree of accuracy than that with which the weight of a cubic decimeter of water can be determined, the mass of platinum kept at Paris is the real standard on which all metric weights are based. The following table illustrates the metric units of mass:

1 gram (g) = 1,000 milligrams (mg).

1 gram = 100 centigrams.

1 gram = 10 decigrams.

1 gram = $\frac{1}{1000}$ kilogram.

(3) The unit of mass in the English system is the pound which is equal to 453.59 grams.

c. Unit of time (T).—(1) Because of the earth's exact periodic movement, it is easy to see why the standard of time chosen is that which the earth requires for a single rotation around on its axis. More exactly, it is the mean time elapsing between successive transits of the sun across the meridian at any one place. This period (mean solar day) is divided into 24 hours, every hour into 60 minutes, and every minute into 60 seconds.

(2) The unit of time in both the C. G. S. and English systems is the mean solar second or one 86, 400th part of a mean solar day.

16. Derived units.—Derived units, as explained, are those like speed which are dependent upon one or more of the fundamental units.

a. Density (d).—(1) Density is the mass or quantity of matter of a substance per unit of its volume. In the C. G. S. system it is expressed in grams per cubic centimeter, while pounds per cubic foot is the measure used in the English system. The density of water at 4° C. is 1 gram per cubic centimeter in the C. G. S. system and 62.5 pounds per cubic foot in the English system. The density of air at 0° C. and a pressure of 76 cm. of mercury is 0.00129 gm. per cc and in the English system is 0.075 lb. per cubic foot.

(2) The value of the density of the air, 0.00129 gm. per cc, implies that if all elements (nitrogen, oxygen, argon, etc.) within the space of 1 cubic centimeter could be picked out and weighed, their total weight would come to 0.00129 grams.

(3) Since $d = \frac{m}{v}$, $m = vd$. Thus, knowing the volume of a body and looking up its density in a table, it is possible to calculate its mass. Likewise, knowing the mass and density, the volume can be calculated, since $v = \frac{m}{d}$.

$$v = \frac{m}{d} = \frac{\text{grams}}{\frac{\text{grams}}{\text{cc}}} = \text{grams} \frac{\text{cc}}{\text{grams}} = \text{cc}.$$

From the above, it is seen that volume comes out in the right units (cc).

b. Velocity (V).—(1) Velocity is defined as the distance traveled per unit of time. If, then, s is the distance traveled per unit of time t ,

$$V = \frac{s}{t} = \frac{\text{cm}}{\text{sec.}} = \frac{\text{ft.}}{\text{sec.}} = \frac{\text{miles}}{\text{hour}}.$$

(2) By means of this equation we can find the value of any one of the quantities in it if the other two are known. For example, if an airplane traveling at 100 miles per hour took 5 hours to go in a direct line from Randolph Field to New Orleans, the distance between these two places would be—

$$s = Vt = (100 \text{ mph}) (5 \text{ hr.}) = 500 \text{ miles}.$$

(3) Here the unit of time is 1 hour and the unit of velocity is 100 miles per hour. Assuming that the plane's velocity was constant, it flew 100 miles for each unit of time of which there were 5, making a total of 500 miles flown.

c. Acceleration (a).—(1) Acceleration is the rate of increase or decrease of velocity. It is defined by the equation:

$$a = \frac{v}{t} \text{ (} v \text{ is the change in velocity during a time } t \text{)}.$$

(2) The units of acceleration in both the English and C. G. S. systems are easy to understand.

(a) *English system.*

$$a = \frac{v}{t} = \frac{\left(\frac{1 \text{ ft.}}{\text{sec.}}\right)}{\text{sec.}} = 1 \text{ foot per second per second}$$

or:
$$a = \left(\frac{1 \text{ ft.}}{\text{sec.}}\right) \left(\frac{1}{\text{sec.}}\right) = \frac{1 \text{ ft.}}{(\text{sec.})^2} = 1 \text{ foot per second squared}.$$

(b) *C. G. S. system.*

$$a = \frac{\left(\frac{1 \text{ cm}}{\text{sec.}}\right)}{\text{sec.}} = 1 \text{ cm per second per second}$$

or:
$$a = \left(\frac{1 \text{ cm}}{\text{sec.}}\right) \left(\frac{1}{\text{sec.}}\right) = \frac{1 \text{ cm}}{(\text{sec.})^2} = 1 \text{ cm per second squared.}$$

(3) Thus, if a body starts from rest and at the end of the first second has a velocity of 10 feet per second and at the end of the second second has a velocity of 20 feet per second, and at the end of the third second has a velocity of 30 feet per second, its acceleration is 10 feet per second per second.

$$a = \frac{v}{t} = \frac{\frac{10 \text{ ft.}}{\text{sec.}}}{\text{sec.}}$$

QUESTIONS AND PROBLEMS

1. What are the three fundamental units and why are they so called?
2. What are derived units?
3. Why is the metric (French) system more logical and better adapted to every practical and scientific purpose?
4. What are the fundamental units in the French and English systems?
5. 1 meter is equal to how many decimeters? centimeters? millimeters?
6. 10 miles equal how many kilometers?
7. Change 755 milligrams to grams.
8. Change 1,540 grams to kilograms.
9. A girl weighs 52.5 kilograms. Express her weight in pounds.
10. How many liters does a tank hold which is 6 meters long, 1.5 meters wide, and 1 meter deep? How many cubic centimeters does it hold?
11. Define velocity; acceleration.
12. In his transatlantic flight from New York to Paris in 1927, Lindbergh traveled 3,630 miles in 33.5 hours. What was his average speed?
13. A ball rolling down an incline has a velocity of 60 cm. per second at a certain instant and 11 seconds later it has attained a velocity of 181 cm. per second. Find its acceleration.
14. A body having an initial velocity of 60 cm. per second has an acceleration of -32 feet per second per second. Find the velocity at the end of 1, 2, and 3 seconds.

15. A railroad train having a velocity of 40 miles per hour is brought to rest in 1 minute. Find the acceleration in feet per second per second.

SECTION IV

BALANCED FORCES

	Paragraph
Scalar and vector quantities.....	17
Components of vectors.....	18
Calculations with vectors.....	19
Forces and their balance.....	20

17. Scalar and vector quantities.—*a.* A large number of the quantities with which physics deals are of such a nature that they are called vector quantities. This means that in order to be completely defined, both a direction and a magnitude must be specified. For instance, we may say that an airplane is moving at a rate of 300 miles per hour, but we really do not know all about its motion until we specify the direction in which it is flying. The “300 miles per hour” is the speed, but in order to determine the velocity we must say that it is moving 300 miles per hour north-northeast, as an example. Velocity is a vector quantity, but speed is a scalar quantity. Scalars are another group of physical quantities distinguishable from vectors because no direction may be ascribed to them. Vectors, then, are quantities which have direction as well as magnitude. Examples are force, acceleration, velocity, and momentum. Scalars are quantities which can be specified by magnitude only. Examples are temperature, energy, volume, mass, time, and power.

b. For convenience in graphical calculations with vector quantities, a system is used whereby an arrow known as a vector is drawn on a graph. The magnitude of the quantity is indicated by the length of the arrow and it is drawn pointing in the direction of the quantity. The point in space where the quantity applies may also be indicated by beginning the arrow at the point of application.

Example: An airplane is passing over Chicago at 300 miles per hour going north-northeast. Show its velocity vectorially using a scale of $\frac{1}{4}$ inch equals 50 miles per hour.

18. Components of vectors.—*a.* In the previous example, the airplane is moving both north and east. The effective speed in the northern direction is known as the northern component of the velocity and similarly, its effective speed in the eastern direction is the eastern component of the velocity. Any vector will have a component or effective value in another direction, except that when the angle

between the two directions is 90° , the component will be zero. The component of a vector in some other direction is defined as its effective value in that direction and is determined graphically by the perpendicular projection of the original vector to the new direction. In other words, lines are drawn perpendicularly to the new direction from

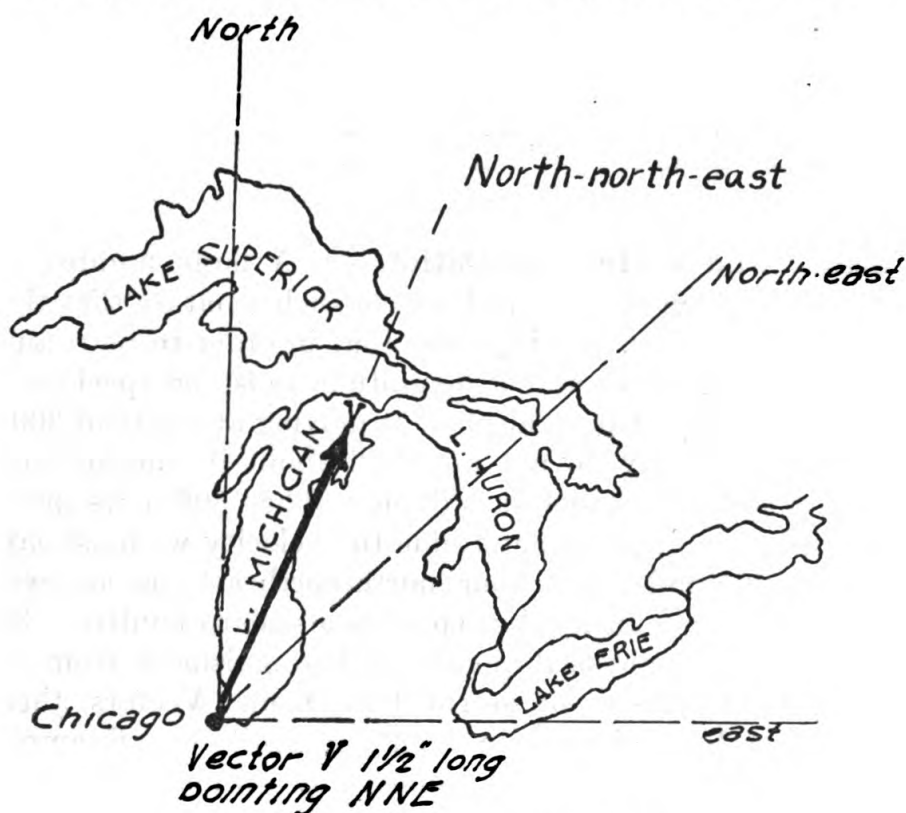


FIGURE 5.—Velocity of airplane as vector.

the beginning and end points of the vector, and the distance between these lines is the component desired.

Example: Find the northern and eastern components of velocity of the airplane in example above.

1 inch = 200 mph scale.

$\frac{1}{16}$ inch = $\frac{1}{16}(200) = 12.5$ mph east.

$1\frac{1}{8}$ inches = $1\frac{1}{8}(200) = 250$ mph north.

b. By mathematical calculation, the component of a vector in another direction is obtained by multiplying the magnitude (length) of the vector by the cosine of the angle separating the two directions.

Example: Solve example above by mathematical calculation.

V to north = $300 \times \cos 22.5^\circ = 300 \times (.924) = 278$ mph

V to east = $300 \times \cos 67.5^\circ = 300 \times (.383) = 115$ mph

c. When calculating with vectors on the two dimensional x - y graph, it is often convenient to break up the vectors into their x and y components. The x component of a vector F will be called F_x and its y component F_y . These two perpendicular components and the coordinate of its starting point will completely determine any vector. In other words, any vector F will be just as completely described by giving these quantities as by giving its length, direction, and starting point. It should be noted that if the end point of the vector is to the left of the starting point, the x component will be negative; and

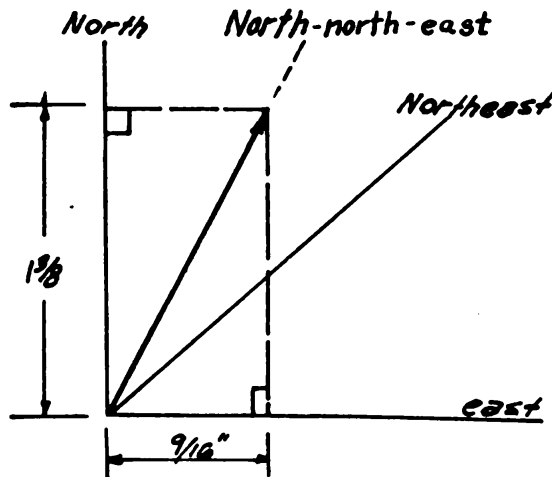


FIGURE 6.—Northern and eastern components of velocity.

if the end point is below the starting point, the y component is negative.

(1) *Example:* Find the x and y components of the vectors shown on the graph in figure 7.

(2) *Example:* Reproduce the vectors from the components given in figure 7.

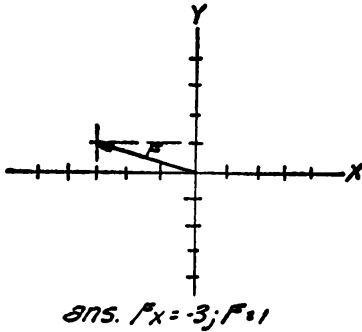
d. By the Pythagorean theorem, the length of a vector is equal to the square root of the sum of $(F_x)^2 + (F_y)^2$, as the vector is the hypotenuse of a right angle triangle whose sides are F_x and F_y . The angle which the vector makes with the x axis is that one whose tangent is F_y divided by F_x .

19. Calculations with vectors.—A special set of rules is required when calculating with vectors, and some of these operations are described below:

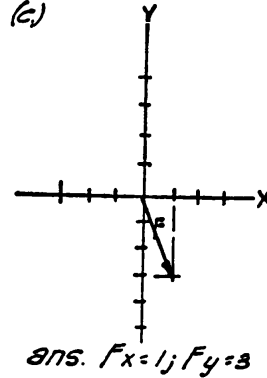
a. *Addition.*—The addition of two or more vectors can be accomplished by first breaking each down into its x and y components. The sum of the vectors will be a new vector, called the resultant, whose x component will be the algebraic sum of the x components of the original vectors and whose y component will be the algebraic sum of

their individual y components. The resultant of several vectors is defined as a single vector which has the same effect as all of the others working together and is the vector sum of all these vectors.

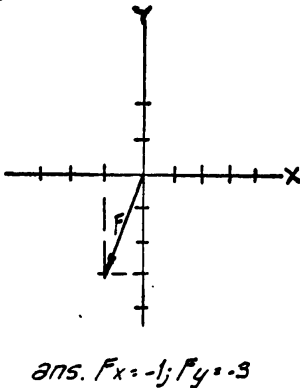
(a)



(c)



(b)



(d)

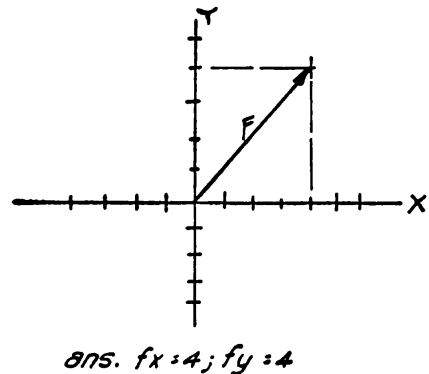
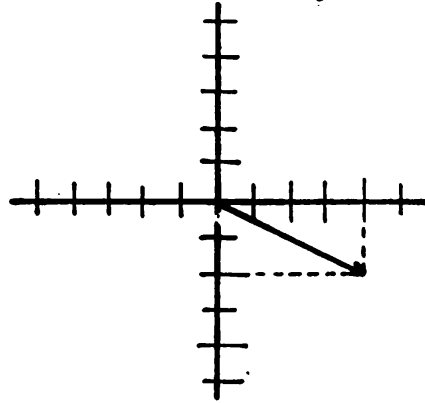
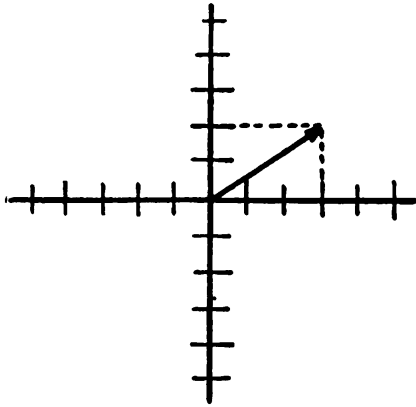


FIGURE 7.—Determination of vector components.

Example: Add the vectors A , B , and C shown on the graph in figure 9 into a resultant vector X .

$$\begin{array}{lcl} A_x = 4 & & \\ B_x = 2 & A_x + B_x + C_x = X_x = 3 & \\ C_x = -3 & & \\ A_y = 1 & & \\ B_y = -3 & A_y + B_y + C_y = X_y = -5 & \\ C_y = -3 & & \end{array}$$

(a) $F_x = 3, F_y = 2$ (b) $F_x = 4, F_y = -2$



(c) $F_x = -4, F_y = -2$ (d) $F_x = -4, F_y = 2$

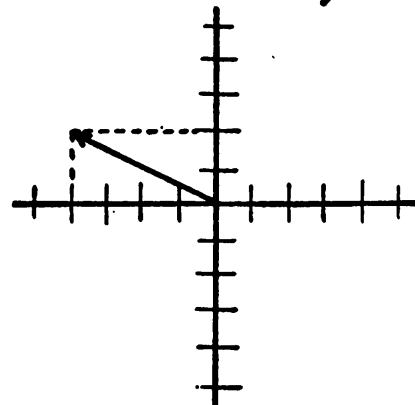
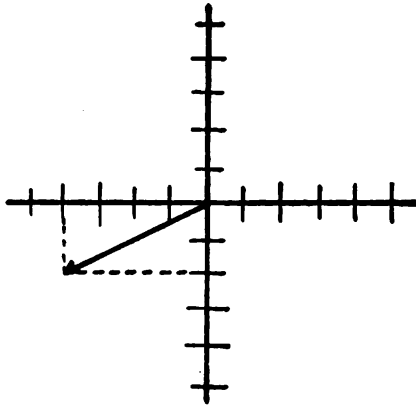


FIGURE 8.—Determination of vectors from components.

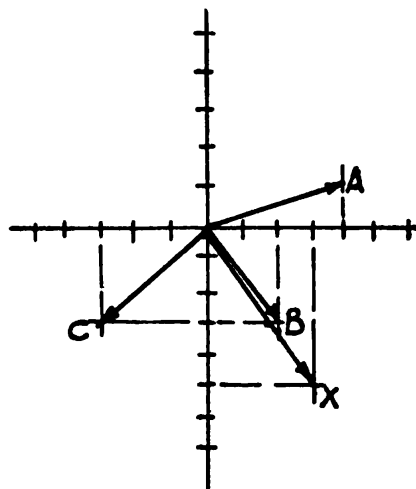


FIGURE 9.—Addition of vectors by addition of components.

b. Addition by parallelogram of vectors.—An interesting result is obtained in the case of the addition of two vectors such as A and B into a resultant vector X as shown in figure 10:

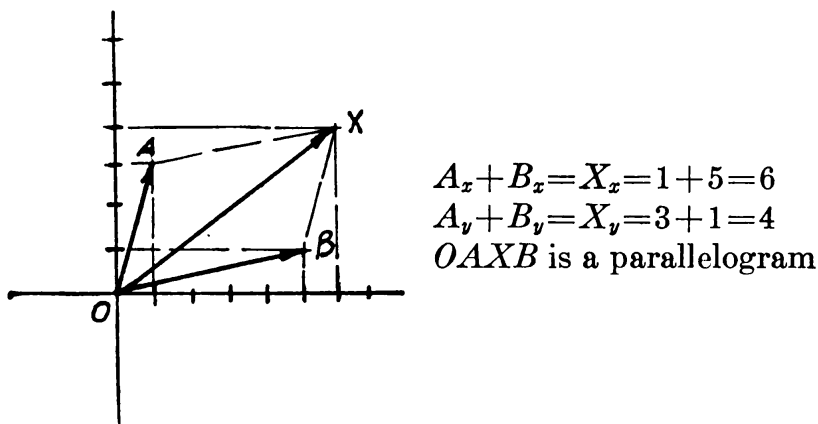


FIGURE 10.—Addition of vectors by completion of parallelogram.

It may be proved that the resultant vector X has the same direction and is equal in length to the diagonal of a parallelogram whose sides are A and B . This points the way for a convenient graphical method of adding two vectors. It is only necessary to complete the parallelogram and draw its diagonal, this diagonal being the desired sum.

c. Parallelogram method for several vectors.—If two vectors are added to obtain a vector resultant, this single new vector will be the complete equivalent of the former two and may be used in their place. If there are three or more vectors to be added, a progressive simplification may be carried out by adding them (by the parallelogram or any other method) two at a time, each addition substituting one vector for two, until only one vector remains. This last vector will be the sum of all the original vectors. The order of the addition is immaterial, but care must be taken that the same vector is not added twice.

Example: Suggest a scheme of addition for five vectors, A , B , C , D , and E .

Add A to B giving a vector M ($M = A + B$)

Add C to D giving a vector N ($N = C + D$)

Add M to N giving a vector O ($O = A + B + C + D$)

Add O to E giving the desired sum ($P = A + B + C + D + E$).

Another solution would be—

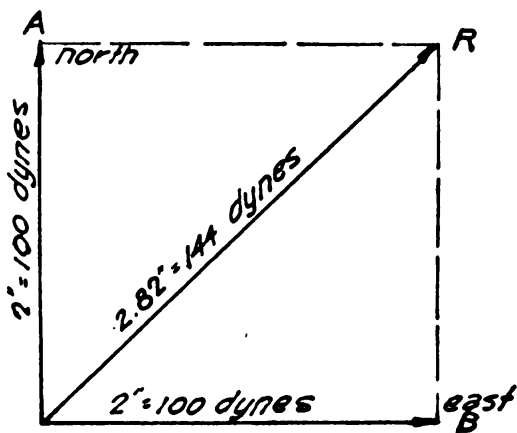
- Add A to B giving a vector P
- Add P to C giving a vector Q
- Add Q to D giving a vector R
- Add R to E giving the desired sum.

20. Forces and their balance.—*a.* All of us are familiar with forces and have some idea as to their effect. If a man's muscles are required to exert forces for a long period of time, he will become fatigued. If a compressional force is exerted on a spiral spring, it will shorten; and the greater the force, the greater the compression. Force could probably be well described as the intensity of "push" or "pull" exerted between one body and another..

b. Physically, force is defined by its effect upon the motion of bodies. According to Newton's laws of motion, a body will remain at rest or will move in a straight line at a constant velocity unless it is caused to change its state of motion by the application of force. The C. G. S. unit of force is the dyne, 1 dyne being sufficient to cause a mass of 1 gram to accelerate 1 centimeter per second per second. In other words, if 1 dyne of force acts on a 1-gram mass for 1 second, the velocity in the direction of the force will be 1 centimeter per second faster than it was before. The dyne is a very small unit, as is shown by the fact that gravity exerts a force of 980 dynes on a 1-gram mass. In English measure, the unit of force is the poundal and is defined in a similar manner; 1 poundal causes a mass of 1 pound to accelerate 1 foot per second per second. Occasionally, for the sake of convenience, the pound weight, the gram weight, etc., will be used for units of force, 1 gram weight, for example, being the force of gravity on 1 gram of mass. The net force of gravity is not constant, changing with the altitude, the geographical location, and the position of the sun and moon. Pound and gram weights are useful units of force when calculating stresses in static cases, but when objects undergo accelerations, the dyne and poundal are much more convenient units for calculation.

c. As mentioned before, force is a vector quantity. When we speak of a thousand dynes of force acting upon an object, we cannot know its effect unless we know the direction in which the force acts. If several forces act upon the body, the rules of vector calculation must be used in order to determine the result. As far as the motion of the body is concerned, the result of these several forces will be the same as though only one force were acting. This effective force will be the vector sum of all the forces acting and will be called the resultant force.

Example: Two forces are applied to a body, each of 100 dynes, one toward the north and one toward the east. What will be the resultant force on the body?



$$A + B = 2.82'' \text{ or } 141 \text{ dynes}$$

$$\text{Scale} = 50 \text{ dynes to } 1''$$

Answer: 141 dynes toward the northeast.

FIGURE 11.—Vector addition of forces.

d. If the vector sum of all the forces acting on a body is zero, the body is said to be in equilibrium, for there will be no tendency for acceleration in any direction. This equilibrium condition is merely a balance between all of the forces so that there is a general cancelation by oppositely directed forces. Suppose that several forces act on a body and that it is desired to place the body in equilibrium. This may always be done by applying an additional force of the correct direction and magnitude to cause general cancelation, so that the final vector sum will be zero. This additional force necessary for equilibrium is called the equilibrant. It will always be equal in magnitude to but opposite in direction from the resultant of all the other forces acting.

e. Mathematically, the criterion for equilibrium of several forces is that the algebraic sum of their x components must equal zero and the algebraic sum of their y components must equal zero. Likewise, the x and y components of the equilibrant of several unbalanced forces must be the negative of the x and y components respectively of their resultant.

(1) *Example:* Show in two ways that the following forces are in equilibrium.

(a) *Graphical solution.*—See figure 12.

(b) *Mathematical solution.*

$$A_x + B_x + C_x = 2 + 5 - 7 = 0$$

$$A_y + B_y + C_y = 2 - 2 + 0 = 0$$

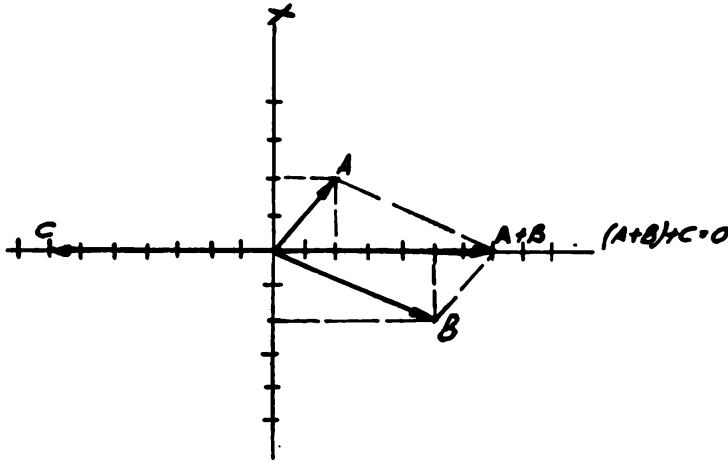


FIGURE 12.—Graphical addition of forces.

(2) *Example:* Find in two ways the equilibrant of the following forces A , B , C :

$$\begin{array}{lll} A_x=2 & B_x=3 & C_x=1 \\ A_y=2 & B_y=-1 & C_y=-4 \quad (\text{all values in pounds}) \end{array}$$

Solution: Let the equilibrant be a vector X .

(a) *Graphical solution.*

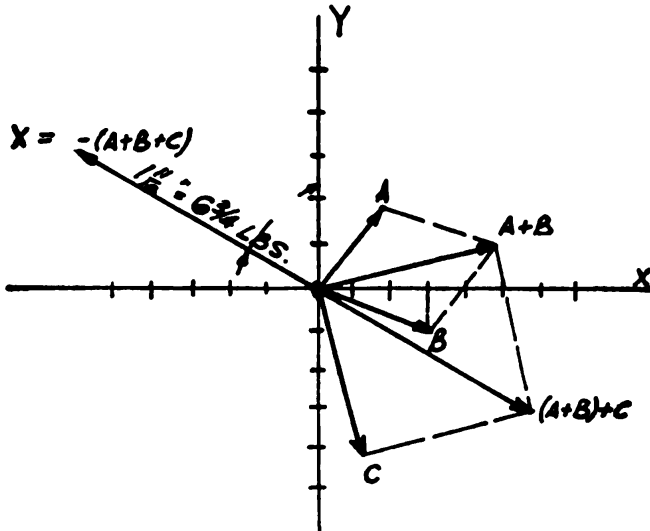


FIGURE 13.—Addition of several forces by parallelogram method.

(b) *Mathematical solution.*

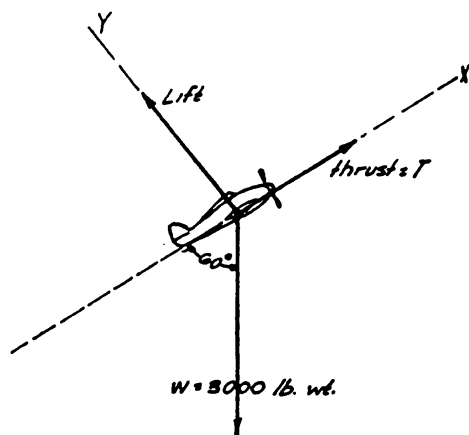
$$\begin{aligned} X_x &= -(A_x + B_x + C_x) = -6 \text{ lb.} \\ X_y &= -(A_y + B_y + C_y) = 3 \text{ lb.} \\ X &= \sqrt{36 + 9} = \sqrt{45} = 6.7 \text{ lb.} \end{aligned}$$

f. If any body remains at rest or moves at a constant velocity, the forces acting on the body must be in equilibrium; otherwise there will be an acceleration of the body in the direction of the resultant

of all the forces acting. In calculating the forces on actual physical bodies, the calculator should be careful to see that none are omitted from consideration. The following illustrative examples show how some vector calculations may be accomplished:

(1) *Example:* Suppose a superpowered pursuit plane weighing 3,000 pounds can climb steadily upward at a 30° angle. What will be the thrust of the propeller when climbing at this angle? Assume for simplification that the lift of the wings is perpendicular to the line of flight and that there is no drag due to air resistance.

Solution: In this case it will simplify the work if the x axis is drawn parallel to the line of flight as shown on the diagram:



$$\begin{aligned} W_x + T_x &= 0 = W_x + T \\ W_x &= 3,000 \cos 60^\circ = -1,500 \\ -1,500 + T &= 0 \\ T &= 1,500 \text{ lb.} \end{aligned}$$

FIGURE 14.—Balance of forces on airplane in flight (simplified).

The lift need not be considered in setting up the balance for equilibrium in the x direction, as the lift will have no x component with this orientation of the axes. The x component of the gravity force will be $-3,000 \text{ times } \cos 60^\circ$ or $-1,500$ pounds. As the sum of the x components must be zero, the thrust of the propeller must be also equal to 1,500 pounds.

(2) *Example:* An airplane pilot wishes to fly straight north. A wind is blowing from the east at 50 miles per hour and the cruising air speed of the plane is 200 miles per hour. In what apparent direction (with respect to the air) must he fly, and what will be his actual northward velocity?

Solution: The actual velocity of the plane with respect to the ground will be the vector sum of the wind velocity plus the velocity of the plane with respect to the air. This resultant vector must have a direction of true north. The conditions of the problem will be satisfied if the x component of the resultant velocity is zero and the y component is finite and positive. These conditions will be satisfied if the apparent velocity is in a direction between north and east and such that its x component is equal to the wind speed. Draw axes with

positive x to the east. Using a scale of $\frac{1}{2}$ inch for 50 miles per hour, draw wind vector W . With a radius of 2 inches (200 mph) draw an arc through the northeast quadrant. The velocity vector of the plane with respect to the air will be called W , and must terminate on this arc. Its x component must also have a value of $\frac{1}{2}$ inch (50 mph); so draw a perpendicular to the x axis at a distance of $\frac{1}{2}$ inch. The apparent velocity vector with respect to the air must terminate at the intersection of the arc and the perpendicular as in the figure to follow. The resultant vector will be in the desired direction and its y component will indicate the actual northward velocity.

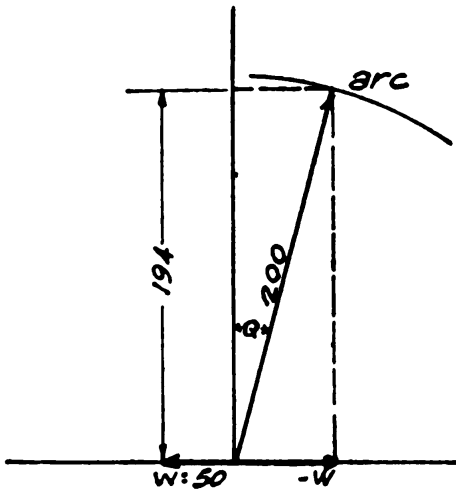


FIGURE 15.—Correction for crosswind in airplane flight.

$$\text{Angle } Q = \sin^{-1} \frac{50}{200} = 14.5^\circ \text{ from N;}$$

$$V_n = 200 \cos 14.5^\circ = 194 \text{ mph.}$$

(3) *Example:* A weight is hung from the center of a 16-foot rope, the ends of which are attached solidly at opposite points 4 feet above the rope's central point. If this rope can stand a tension of 100 pounds, how heavy a weight may be hung at the center?

(a) *Graphical solution.*—Find resultant R of two rope forces by parallelogram method. The equilibrant X will have the same magnitude but opposite direction.

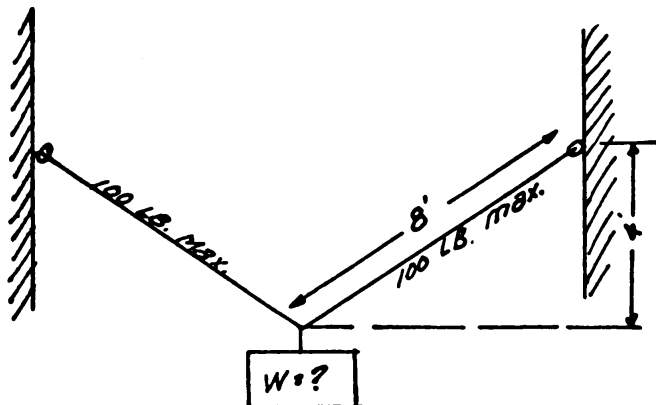


FIGURE 16.—Suspension of weight from center of rope.

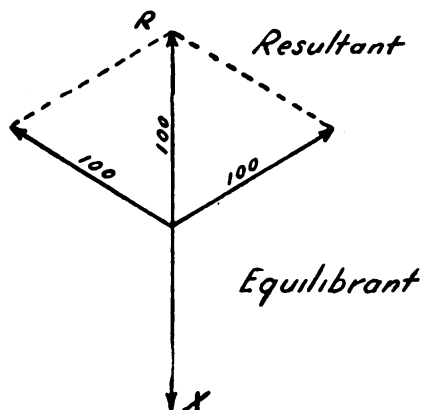


FIGURE 17.—Equilibrium of forces in figure 16.

(b) *Mathematical solution.*—Find the equilibrant of the two rope forces under maximum tension of 100 pounds. With the figure drawn and labeled as in figure 17, let W be the equilibrant. From conditions of symmetry, and vertical nature of gravity, W_x will be zero.

$$W_y = -(A_y + B_y) = -50 = 50 = 100 \text{ pounds.}$$

Therefore, W must not exceed 100 pounds.

PROBLEMS

1. The wind resistance of a human body falling through the air may be approximately expressed as $R = .01V^2$. This resistance is in pounds of force resisting the motion downward and V is in miles per hour. After falling for a short time, the body attains a constant velocity. What will be this velocity for a man weighing 144 pounds?

2. Four different forces act on a body: one of 3 pounds from the north, one of 2 pounds from the east, one of 10 pounds from the west and one of 1 pound from the south. Find graphically the resultant of these forces by addition, using two different sequences of the individual additions. Show that these results are the same and that they coincide with the result of mathematical calculation.

3. Displacement is a vector quantity, as are force and velocity. A hiker found that he was lost. He could remember that he had made his hike in three parts but could not remember the order in which they were made. One part was a walk northwest for 3 minutes, one due north for 20 minutes, and one southeast for an hour. If he always walked at the same speed, which way and for how long should he walk to get to his starting point? Hint: The walk home would be an additional vector which would cause the resultant displacement to be zero.

4. Find the resultants and the equilibrants of the following sets of forces. All directions are in degrees clockwise from the y (north) axis:

- | | |
|---------------------------|------------------------------|
| a. 0° 10 pounds | c. 350° 5, 000 pounds |
| 100° 40 pounds | 120° 5, 000 pounds |
| b. 10° 1,000 dynes | 240° 5, 000 pounds |
| 50° 750 dynes | d. 10° 1, 000 pounds |
| 270° 900 dynes | 100° 1, 000 pounds |
| 180° 500 dynes | 235° 1, 414 pounds |

5. A 500-pound weight hangs from a support as shown in figure 18. What is the tension in the horizontal rope and the compressional force in the beam?

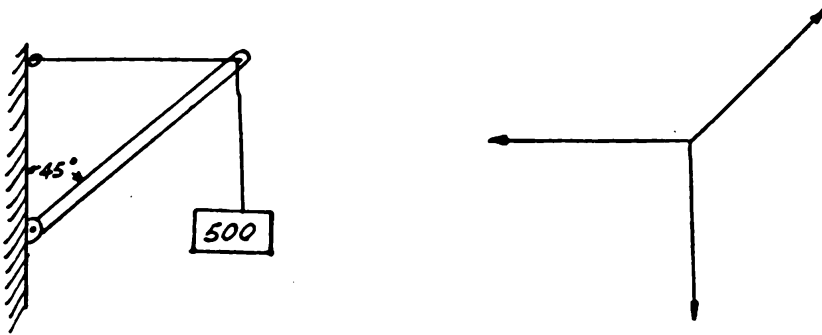


FIGURE 18.—Suspension of weight from equilibrium of forces.

6. A 500-pound weight hangs from a support as shown in figure 19. What is the tension in the upper rope and the compressional force in the beam?

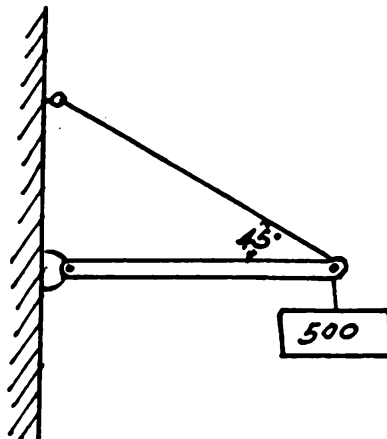


FIGURE 19.—Suspension of weight by horizontal beam.

7. A boy pulls a sled as shown in figure 20. The sled and passenger together weigh 110 pounds. There is one-tenth of a pound of resisting

force R for every pound of perpendicular force between the runners of the sled and the ground. How hard will the boy have to pull on the rope?

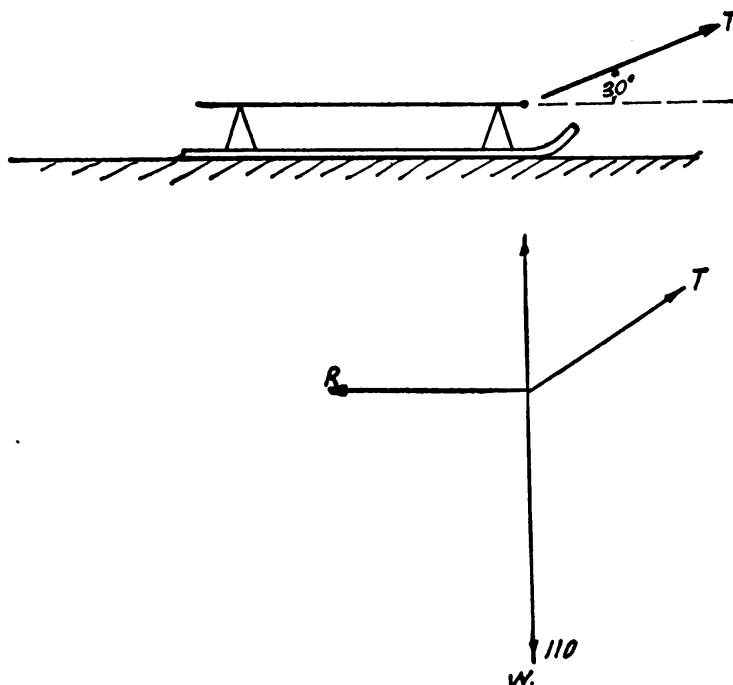


FIGURE 20.—Equilibrium of forces in pulling of sled.

SECTION V

ACCELERATED MOTION

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Motion under constant linear acceleration.....	22
Momentum and impulse.....	23
Conservation of momentum.....	24
Centripetal force.....	25
Illustrative examples.....	26

21. Laws of motion.—*a.* Kinetics is the study of bodies in motion and deals with relationships between forces, velocities, and accelerations. The fundamental basis for this study is found in Newton's three laws of motion. The first law states that bodies in motion will continue in a straight line at a constant speed unless forced to change their velocity by the application of force. A necessary corollary of this law is that bodies at rest will remain at rest unless there is an unbalanced force acting. This is the familiar principle of inertia. Inertia is that property of a body which makes it resist a gain or loss of velocity. A common example of the effect of inertia occurs when an automobile's brakes are suddenly and strongly applied. The passenger must brace himself or he will strike the windshield because

his own inertia tends to keep him in motion even though the car is stopping.

b. A second law expresses the mathematical relationship between force, mass, and acceleration. This law states that the acceleration of any body is directly proportional to the force applied and inversely proportional to the mass of the body. This may be expressed by the formula:

$$a = \frac{f}{m}, \text{ or } f = ma$$

c. When C. G. S. (metric) units are used, force is expressed in dynes, mass in grams, and acceleration in centimeters per second per second. As a matter of interest, this is the way force is defined—by its effect upon the motion of one gram to be accelerated one centimeter per second per second.

d. The above relationship holds equally well with English units, provided that the force is expressed in poundals, the acceleration in feet per second per second, and the time in seconds. The poundal is defined as the force which will give a pound mass an acceleration of 1 foot per second per second. The poundal is such a small unit that 32.2 of them are required to produce the same force as that of gravity on a 1-pound weight, for a poundal equals approximately one-half ounce of weight.

e. The last section discussed the properties of vectors and forces. Both acceleration and force are vector quantities, and all the laws of vector calculation apply to them. The acceleration of a body will always be in the same direction as the resultant of all the forces acting upon it, and the magnitude of the acceleration vector will be equal to the magnitude of the resultant force vector divided by the mass of the body being accelerated. This rule will always apply, even though the body may already have a velocity in some other direction. The time rate of change of the velocity of a body will be its acceleration, whether this change be in the magnitude of the velocity vector, or in its direction, or both. Suppose a body travels in a circular path at a constant speed. The velocity under these conditions is always changing direction in such a way that there is an acceleration toward the center of the circle. A force called the centripetal force is required to hold the body in its path.

f. Newton's third law states that for every action there is always an equal and opposite reaction. This means that when two bodies are acting on each other, the force on one is equal to the force on the other but acting in the opposite direction. When a man jumps from a boat, the boat is pushed backward with the same force that pushes the man forward.

22. Motion under constant linear acceleration.—*a.* Occasionally the force acting on a body has a constant direction and a constant intensity, and produces a constant acceleration. The most common force of this type is gravity. Gravity exerts a force of approximately 980 dynes for each gram of mass and about 32.2 poundals for each pound of mass. Consequently, bodies under the influence of gravity fall with an acceleration of 980 centimeters per second per second or 32.2 feet per second per second. This may be expressed mathematically as

$$a = \frac{f}{m} = \frac{980}{1} = 980 \text{ cm. per second per second.}$$

If a body initially at rest is given a constant acceleration, the velocity will increase linearly with time according to the following formula:

$$V = at$$

(where a is acceleration, V is the velocity, and t is the time).

In case there is an initial velocity V_o , the formula would be:

$$V = V_o + at.$$

Example: A body is accelerating at the rate of 10 feet per second. Seven seconds ago its velocity was 18 feet per second. What is it now?

Solution: By the definition of acceleration, its velocity will be 10 feet per second faster, for each second that the acceleration is operating. Its final velocity will then be 18 plus 7 times 10 or 88 feet per second.

b. Suppose we wish to know how far the body traveled in the seven seconds of the above example. One method of calculation would be to find the average velocity and multiply by the time of action. The average velocity will be one-half the sum of the initial and final velocities, or 53 feet per second. The distance then would be 53 times 7 or 371 feet. In case the body had started from rest with any acceleration a , the average velocity would be merely one-half of the final velocity or one-half of a times t , where t is the time of action. Then the distance traveled would be:

$$\frac{1}{2}at^2 \text{ (multiplying this average velocity by the time).}$$

c. We now have two formulas for the motion of bodies starting from rest under a constant acceleration.

$$(1) V = at.$$

$$(2) d = \frac{1}{2}at^2 \text{ (} d \text{ is the distance traveled in time } t \text{).}$$

d. By algebraic transformation between these relations we can get another equation showing the relationship between velocity and distance for the case of constant acceleration from rest.

$$\text{Square } V^2 = at^2. \quad (1)$$

$$\text{Multiply by } a, ad = \frac{1}{2}at^2. \quad (2)$$

$$\text{Substitute } ad = \frac{1}{2}V^2.$$

$$\text{Then: } V^2 = 2ad. \quad (3)$$

e. With the equations in d(1), (2), and (3) above a variety of problems involving accelerated motion may be solved. These formulas apply with any constant linear acceleration a , provided the body is at rest when the time is zero.

(1) *Example:* A bomb is dropped from an airplane at 3,000 feet. How long will it take to reach the ground? (Neglect resistance of air.)

Solution: d is 3,000 feet; a is 32.2 feet per second.

Use formula (2) (d above):

$$3,000 = \frac{1}{2}(32.2)t^2$$

$$t^2 = (3000)2/32.2 = 186$$

$$t = \sqrt{186} = 13.6 \text{ seconds.}$$

(2) *Example:* An automobile starts from rest at constant acceleration. After traveling 1,000 feet it reaches a velocity of 90 feet per second. What was the acceleration?

Solution: Use formula (3) (d above):

$$V^2 = 2ad.$$

$$90^2 = 2a(1,000)$$

$$a = \frac{8100}{2000} = 4.05 \text{ feet per second per second.}$$

(3) *Example:* A force of 500 pounds is used to lift a weight of 450 pounds. How long will it take to lift the weight 300 feet?

Solution: The force downward from gravity will be 450 pounds; so the net force up will be 50 pounds. As one pound is 32.2 poundals, the net force up will be 50×32.2 or 1,610 poundals.

$$a = \frac{f}{m} = \frac{1610}{450} = 3.58 \text{ feet per second per second}$$

$$d = \frac{1}{2}at^2 = 300 = \frac{1}{2}(3.58)t^2$$

$$t^2 = 167$$

$$t = \sqrt{167} = 12.9 \text{ seconds.}$$

23. Momentum and impulse.—*a.* A concept concerning moving bodies called momentum may be understood as a “quantity of motion.” It is defined as the mass of the body multiplied by its velocity. It is a vector quantity, having a magnitude as defined above and a direction which coincides with that of the velocity. A concept related to momentum is impulse. When a force acts for a period of time, the result is known as an impulse. Impulse is also a vector quantity whose magnitude is the product of the magnitude of the force and the time of its action. Its direction is the same as that of the force applied.

$$\text{Impulse} = (\text{force}) \times (\text{time}).$$

$$\text{Momentum} = (\text{mass}) \times (\text{velocity}).$$

b. If a force of f dynes is applied on a body of mass m for t seconds, an impulse of $(f)(t)$ dyne seconds will likewise be applied. It may also be proved that this impulse will produce a change in momentum of $(f)(t)$ gram centimeters per second. The change in momentum has a value identical with that of the impulse required to produce it.

$$(f)(t) = (V - V_o)$$

(V is final velocity; V_o is initial velocity.)

$$(f)(t) = mv$$

(v is change in velocity.).

Example: A fire hose has a nozzle with a radius of 1 centimeter and squirts a stream with a velocity of 2,500 cm per second. The stream is directed perpendicularly against a wall. What will be the force in kilograms against the wall if we assume that none of the water rebounds?

Solution: During a time of 1 second—

The total volume of water will be $2,500 \times (\pi)r^2 = 7,850 \text{ cm}^3$.

Total mass of water will be 7,850 grams.

Total momentum lost will be $(7,850)(2,500)$ or 19,600,000 gram centimeters per second.

Impulse required will be also 19,600,000 dyne seconds.

If this impulse is given in 1 second, the force must be 19,600,000 dynes.

1.96×10^7 is also 20,000 grams at 980 dynes per gram.

20,000 grams is also 20 kilograms of force.

24. Conservation of momentum.—*a.* Newton's third law states that action and reaction are equal whenever two bodies act on each other. As the action and the reaction must act at the same time, the two bodies must gain equal but oppositely directed impulses during the time of contact. If the two bodies may be considered alone, so that there are no outside influences, they will gain equal but oppositely directed changes in momentum and the vector sum of the

changes in momentum will be zero. In an isolated system, then, it is impossible for any change in the total momentum to take place without some force being applied from the outside. If a gun is fired while resting on a smooth (frictionless) table, the gun in its recoil will gain the same amount of momentum as the bullet received in the forward direction.

(1) *Example:* A gun fires a 1-ounce bullet at 3,000 feet per second. If the gun weighs 7 pounds, what will be its recoil velocity?

$$m_1v_1 = m_2v_2 \text{ (} m \text{ is momentum)}$$

$$\frac{1}{16}(3,000) = 7v$$

$$v = \frac{3,000}{(7)(16)} = 26.8 \text{ feet per second.}$$

(2) *Example:* If the bullet above imbeds itself in a block of wood weighing 5 ounces, how fast will the block and bullet together move after impact?

Solution: The momentum of the block and bullet together after impact must be equal to the momentum of the bullet alone before the impact.

$$m_1v_1 = (m_1 + m_2) v_2$$

$$v_2 = \frac{m_1v_1}{m_1 + m_2} = \frac{(1)(3,000)}{1 + 5} = 500 \text{ feet per second}$$

b. In case the forces and velocities are in various directions, the rules of vector calculation will be used; the sum of the x components and the sum of the y components of the total momentum will be conserved. That is, the vector sum of the momentum of the bodies will remain constant throughout the action, provided there are no outside forces acting.

Example: Two putty balls collide as shown in figure 21. What will be the speed after impact if the balls stick together?

$$v_1 = 2 \text{ cm. per second}$$

$$m_1 = 3 \text{ gr.}$$

$$v_2 = 4 \text{ cm. per second}$$

$$m_2 = 2 \text{ gr.}$$

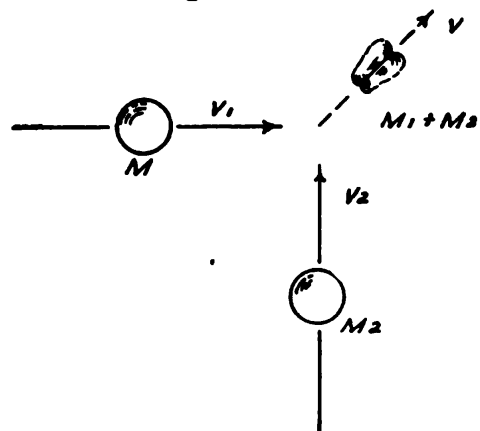


FIGURE 21.—Inelastic impact of two putty balls.

Momentum in y direction $= 4 \times 2 = 8$ gr. cm. per second.

Momentum in x direction $= 3 \times 2 = 6$ gr. cm. per second.

With new total mass of 5 grams:

Final velocity in x direction $= \frac{6}{5}$ cm. per second.

Final velocity in y direction $= \frac{8}{5}$ cm. per second.

Final speed $= \sqrt{\left(\frac{6}{5}\right)^2 + \left(\frac{8}{5}\right)^2} = \sqrt{\frac{100}{25}} = 2$ cm. per second.

c. The importance of this concept of action and reaction may be seen in many principles of mechanics. The propeller on an airplane pushes backward on the air, providing forward pull on the plane to overcome air resistance and wing drag, and to provide acceleration when the speed is increased. Rocket propulsion is possible because the force which ejects the gases out the back also pushes the rocket forward.

25. Centripetal force.—According to Newton's first law, forces are required to change the direction as well as the magnitude of the velocity of a body in motion. If a body travels at constant speed in a curved path, it is being accelerated whether or not the speed is being changed. This acceleration due to the curvature is always in a direction perpendicular to the path. The magnitude of acceleration will be equal to the square of the speed divided by the radius of curvature at that point. A force called the centripetal force must be applied on the body toward the center of curvature in order to hold the body in a curved path. If this force is released, the motion will continue in a straight line at a tangent to the original arc. If the acceleration toward the center is $\frac{v^2}{R}$ the force (centripetal) applied will

be $\frac{mv^2}{R}$. m is the mass of the body in grams. v is the velocity of the body in tangential direction in centimeters per second. R is the radius of curvature in centimeters; then the force f will be expressed in dynes.

26. Illustrative examples.—a. A bomber flies 300 miles per hour at 30,000 feet. If we assume wind resistance is negligible, how far from the target must the bombs be released?

Solution: The vertical and horizontal motions are quite independent. That is, the motion downward will follow the normal rules of acceleration under gravity and the horizontal velocity during the fall will remain constant at 300 miles per hour. The problem is then to find

how far an object will move at 300 miles per hour during the time necessary for a normal fall of 30,000 feet.

$$d = \frac{1}{2} at^2$$

$$d = 30,000 = \frac{32.2}{2} t^2$$

$$t = \sqrt{\frac{60,000}{32.2}} = \sqrt{1862} = 43.1 \text{ seconds time for fall}$$

$$43.1 \text{ seconds} = \frac{43.1}{60 \times 60} \text{ or } .0120 \text{ hour.}$$

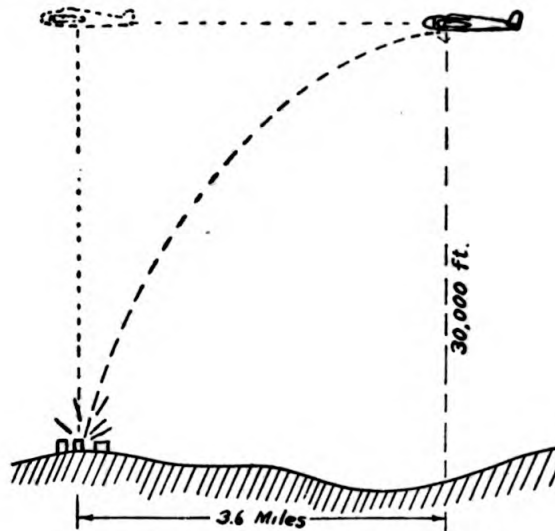


FIGURE 22.—Bombing from horizontal flight.

Horizontal distance traveled will then be $.012 \times 300$ or 3.60 miles.

b. Three weights are strung as shown in the diagram. If we assume there is no friction, how far will they move in 3 seconds after release?

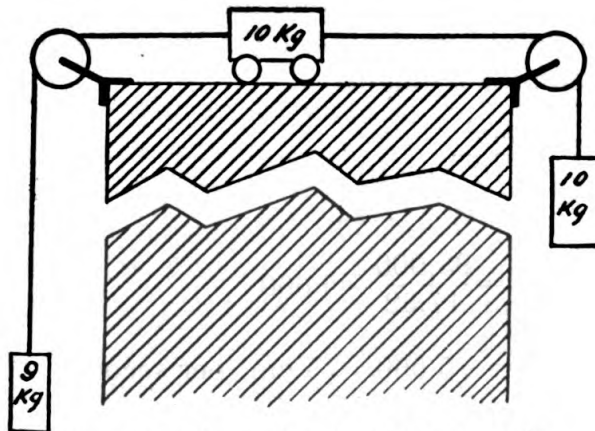


FIGURE 23.—Acceleration of unbalanced weights.

Solution: There is 1 kilogram of unbalanced force on the system and 29 kilograms of mass to be accelerated.

$$a = \frac{f}{m}$$

$$f = 1,000 (980) = 980,000 \text{ dynes}$$

$$m = 29,000 \text{ gr.}$$

$$a = \frac{980,000}{29,000} = 33.8 \text{ cm. per second per second}$$

$$d = \frac{1}{2} at^2 = \frac{33.8(9)}{2} = 152 \text{ cm.}$$

c. A 1-gram weight hangs from a string 20 centimeters long and is whirled as shown in figure 24. If the weight holds itself out at a distance of 10 centimeters, how fast is the weight moving?

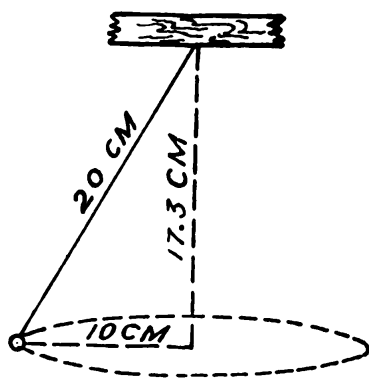


FIGURE 24.—Pendulum with circular motion.

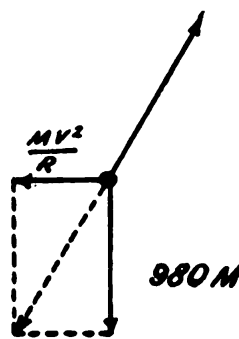


FIGURE 25.—Vector force balance for figure 24.

Solution: Set up a force balance as shown in figure 25. The resultant of the force of gravity and the centrifugal force (equal and opposite to centripetal force) must be in the same direction as that of the string. By similar triangles

$$\frac{mv^2}{10} = \frac{10}{980m}$$

$$v^2 = \frac{98,000}{17.32} = 5,660$$

$$v = \sqrt{5,660} = 75 \text{ cm. per second.}$$

d. An airplane makes a loop of 100-meter radius. How fast must the plane be traveling in order that the pilot, who forgot to fasten his safety belt, will not fall out at the top of the loop?

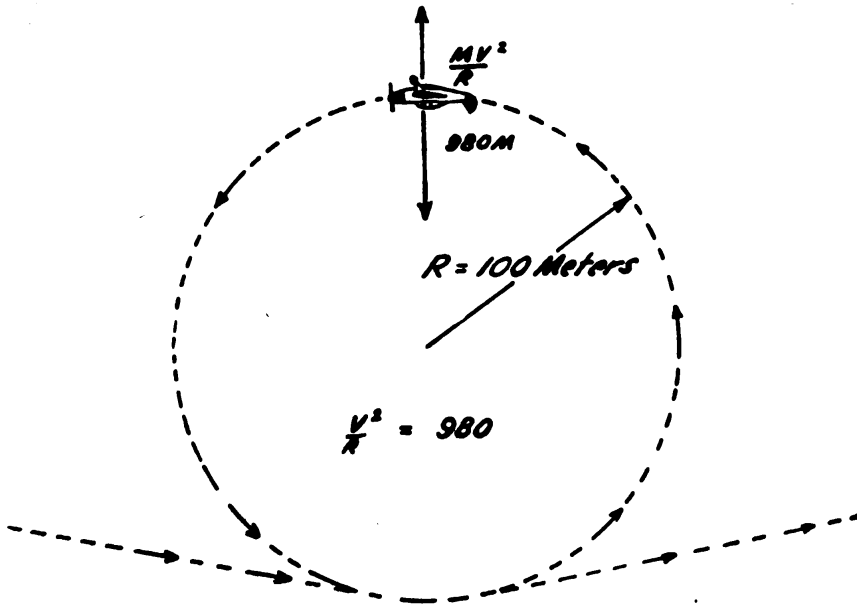


FIGURE 26.—Balance of forces in airplane loop.

Solution: Centrifugal force must equal gravity or $\frac{v^2}{R} = g$.

$$v^2 = 980 (10,000)$$

$$v = \sqrt{9,800,000} = 3,130$$

$$v = 3,130 \text{ cm. per sec.} = 31.1 \text{ meters per second.}$$

PROBLEMS

1. A freight train can accelerate at 1 foot per second per second and can stop by braking with an acceleration of 5 feet per second per second. If 30 miles per hour is the maximum permissible top speed, how long will the train take to travel between two stations 3 miles apart if it must stop at both of them?

2. An airplane in a perfect turn must be banked so that the resultant force on the plane is perpendicular to the wings. If the plane is banked at a 45° angle and is traveling at 90 meters per second, what is the radius of its circle of turn?

3. Suppose a modern pursuit ship with multiple machine guns can fire 1,200 four-ounce bullets per minute at 3,000 feet per second muzzle velocity. How much additional thrust must the propeller provide if the speed is to remain constant while the guns are firing?

4. A baseball is thrown upward with a speed of 80 feet per second. How high will it go and how long will it take to return to the ground?

5. A certain rubber ball when it strikes the ground rebounds with a velocity three-fourths of that with which it struck. If it is dropped

from a height of 10 feet, how much time will elapse before the ball strikes the ground for the third time?

6. In a delayed parachute jump, the resistance of the air may be considered as $0.01V^2$ pounds when V is in miles per hour. What will be the acceleration of a man jumping from a balloon if his weight is 144 pounds when his velocity is: 0, 100, and 120 miles per hour?

7. If an imaginary rocket ship burns 5 grams of fuel per second, ejecting it as gas with a velocity of 500,000 centimeters per second, what will be the force acting to accelerate the ship in free space?

8. An anchor chain 200 feet long lies on the deck of a boat. The weight of the chain is constant along its length and we may assume that the friction when it slides along the deck is negligible. If one end starts over the edge and it is allowed to fall, what will be its acceleration when (1) 1 foot, (2) 20 feet, (3) 150 feet have gone over?

9. A certain pilot can stand six "g's" of acceleration. If we neglect the acceleration of gravity, what is the minimum radius in which he can turn in a plane doing 350 miles per hour?

10. Suppose a naval plane is shot from a catapult 100 feet long. If a flying speed of 60 miles per hour is attained on the catapult, how many "g's" of constant acceleration must the pilot be able to stand?

SECTION VI

FLUIDS AT REST

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27. Properties of fluids.—*a.* The subject of hydrostatics includes the study of pressure and allied problems in stationary as opposed to moving fluids. We all have so many daily experiences with fluids that their distinguishing property should be readily perceived: Fluids tend to conform to the shape of the vessel in which they are

contained. Solids, the other class of matter, retain their original shape, no matter where they are moved or how they are enclosed. Thus, if we take a hammer out of a box, it will have the same shape as before; but if we pour water out of a bucket, the form alters markedly. A gas will distribute itself evenly throughout an entire container, but a liquid can do so only if enough is admitted to fill the container.

b. Another difference between liquids and gases is their compressibility. It is common knowledge that the air admitted to the cylinder of an aircraft engine readily contracts in volume as the piston moves toward the head. Gases, then, may be compressed almost indefinitely, down to tenths or even millionths of their original volume. If compressed and cooled sufficiently they become liquids. But liquids, on the other hand, are practically incompressible.

28. Pressure in fluids.—*a. Definition of pressure.*—When a fluid is in contact with a solid such as the wall of a container, it exerts a force against this solid. The amount of this force per unit area is the pressure of the fluid. If the fluid exerts 1 dyne of force on 1 square centimeter of area, the pressure is 1 dyne per square centimeter. This same pressure would exert a force of 100 dynes on a wall with 100 square centimeters of area. Other units more commonly used to measure pressure are pounds per square inch, grams or kilograms per square centimeter, atmospheres, inches of mercury, and millibars. An “atmosphere” is the pressure exerted by the standard atmosphere (approximately 15 pounds per square inch); for instance, a pressure of 10 atmospheres would be 10 times the pressure normally exerted by the atmosphere or about 150 pounds per square inch. Inches of mercury and millibars are units commonly used to express the pressure in the atmosphere. A millibar is 1,000 dynes per square centimeter; an inch of mercury as a pressure unit will be explained later in connection with mercurial barometers.

b. Action of pressure.—Though pressure is usually measured by determining the force exerted on a solid wall, pressure may exist within a fluid whether or not a wall is nearby for the fluid to push against. In other words, there is pressure at the center of a pipe as well as at the sides where the force is actually exerted. This pressure within a fluid acts in all directions and therefore is a scalar quantity. Pressure within a fluid may be visualized if one imagines that a thin wall is suddenly built up within the fluid extending in any direction. This wall would have no tendency to move, since the fluid exerts the same force on each side. If the fluid on one side were removed, however, the wall would be forced toward that side by the pressure.

29. Distribution of pressure with depth.—All fluids have weight, and as a result the pressure in any fluid increases with depth. A fluid will exert a force on the bottom of a rectangular container which is equal to the weight of the fluid above. Imagine a horizontal boundary within the fluid at some height above the bottom. The fluid above the boundary is exerting on the fluid below a force equal to the weight of the fluid above. Suppose that a pipe with one unit of cross section area is standing vertically and is filled with water. At any depth in the pipe, the weight of the fluid above is equal to the density of the fluid times the depth at that point; and as this weight acts on a unit area, the pressure must be equal to the density times the depth.

Example: What is the pressure due to weight 100 centimeters below the surface of a pond? Express the result in grams per square centimeter, dynes per square centimeter, millibars, and pounds per square inch.

Solution:

$$\begin{aligned}\text{Density of water} &= 1 \text{ gram per cubic centimeter} \\ &= .036 \text{ pound per cubic inch.}\end{aligned}$$

$$\begin{aligned}\text{Depth of water} &= 100 \text{ centimeters} \\ &= 39 \text{ inches}\end{aligned}$$

$$\begin{aligned}\text{Pressure} &= (\text{density}) (\text{depth}) \\ &= (1) (100) = 100 \text{ grams per square centimeter} \\ &= (.036) (39) = 1.40 \text{ pounds per square inch} \\ &= (100) (980) = 98,000 \text{ dynes per square centimeter} \\ &= \frac{98,000}{1,000} = 98 \text{ millibars.}\end{aligned}$$

30. Buoyancy.—Imagine the fluid within the dotted lines in figure 27 to be enclosed by a thin-walled, practically weightless box. Gravity exerts a force downward on this box of fluid equal to the weight of the fluid enclosed, yet the box remains in equilibrium with no tendency to sink to the bottom. In order that such equilibrium be possible, the fluid outside the box must exert a force upward on the box equal to the weight of the fluid within. If any other substance were placed in the space that the box occupies, it will experience the same upward force because conditions in the fluid outside the space have not changed. This effect was first accurately expressed by Archimedes as follows: "The buoyant or upward force experienced by a body immersed in a fluid is equal to the weight of the fluid displaced by the body." If a body weighs less than the fluid it displaces (has a smaller density), there will be a net force upward, and the body will rise to the top and float. A body which has a greater density than the fluid

will sink to the bottom. The cause of the buoyant force is the difference in hydrostatic pressure between the top and the bottom of the body immersed. Again in reference to figure 27, this difference in pressure is equal to the height of the body times the density of the fluid in which it is immersed. The net force exerted upward is equal to the horizontal cross sectional area multiplied by the difference in

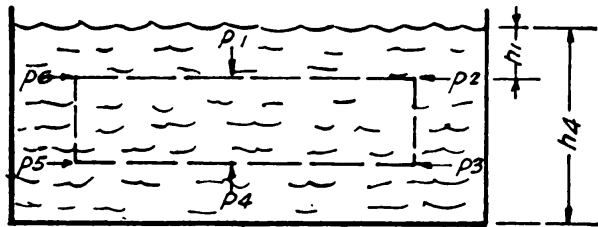


FIGURE 27.—Buoyancy in fluids.

pressure between the top and the bottom of the box. This may be expressed as follows:

$$\begin{aligned}\text{Buoyant force} &= (\text{area}) \times (\text{height}) \times (\text{density}) \\ &= (\text{volume}) \times (\text{density}) \\ &= \text{weight of fluid displaced}.\end{aligned}$$

The buoyant force depends only upon the volume displaced and is in no way influenced by the shape of the body. If two fluids which do not mix readily are placed in the same container, the one with the greater density will sink to the bottom and the lighter fluid will rise. This principle plays an important part in weather, as often in the atmosphere one body of air is forced to rise over another colder and denser mass of air, forming clouds and precipitation.

31. Pressure in fluids under compression.—If an additional pressure is applied to a confined fluid, this pressure is transmitted equally throughout, provided the fluid is at rest. Such pressure applied will be in addition to pressures caused by the weight of the fluid above any specified point. The applications of this principle are innumerable. There are the barber's chair, the hydraulic repair rack at the service station, and also the brakes upon airplanes. In all such cases the operator exerts a force upon a small piston, producing a pressure which is transmitted to a larger piston and exerts upon it a correspondingly larger force. The magnitude of this force is proportional to the area of the piston. The following equation expresses such a relationship:

$$\frac{F_1}{F_2} = \frac{A_1}{A_2}$$

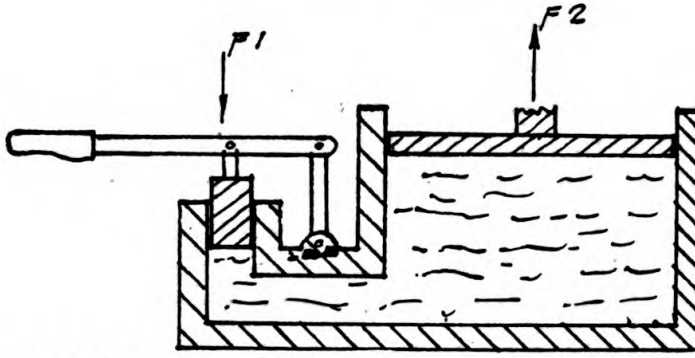


FIGURE 28.—Principle of hydraulic jack. (With the same pressure throughout, the small force F_1 balances the large force F_2 .)

32. Pressure in atmosphere.—*a.* We are interested in the atmospheric pressure for many reasons, particularly for three, as far as the pilot is concerned: Pressure differences across the land produce the winds; pressure measurements give the pilot his altitude; and a study of the pressure configurations over the whole world is one of the best aids in forecasting future weather phenomena.

b. That the atmosphere exerts a pressure upon the earth's surface has long been known. If a long tube is filled with water and inverted, and the excess water allowed to collect in a pool, a column of water 34 feet high would still be left within the tube. This was the first crude barometer. Assuming that a vacuum is left within the tube at the top above the water, the pressure difference between the outside water surface and this vacuum is the atmospheric pressure. This pressure difference will support a column of water within the tube

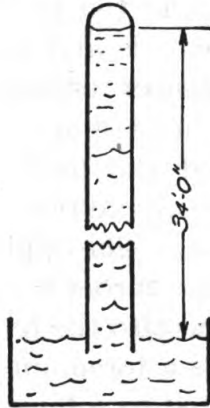


FIGURE 29.—Water barometer.

the height of which depends upon the magnitude of the atmospheric pressure. The difference in pressure between the vacuum at the top and the exposed water surface below is the same as the difference in pressure between the surface of a lake and a depth in the lake corresponding to the height of the water column. The present-day

barometer is based upon the same principle, using mercury, however, instead of water. Because of its greater density, a column of mercury about 30 inches high is sufficient to balance the pressure in the atmosphere.

33. Standard atmosphere.—More precise measurements of the height of the mercury column have shown that the atmospheric pressure varies at any given locality; therefore some average value has had to be arbitrarily set for figuring altitudes and other quantities the accurate estimation of which depends upon atmospheric pressure. The Weather Bureau has accepted 29.92 inches, or 76 cm. of mercury, for standard atmospheric pressure at mean sea level. Scientists have adopted the millibar, which is 1,000 dynes/cm². In these units the standard pressure is 1,013.2 mb or $1,013 \times 10^6$ dynes/cm². The reason we do not feel this pressure is that we create within us a counter-pressure to balance it. It is interesting to note that a sudden and marked lowering of the external pressure, as pursuit pilots can testify, has several undesirable and dangerous physiological effects.

34. Variation of pressure with height.—*a.* The atmosphere, though a gas, is not enclosed in a chamber as is gasoline in a cylinder. Rather it extends into space and is kept from escaping or diffusing by the attraction of each molecule to the earth. The effect of gravity is to cause all molecules to try to fall back to earth, creating a pressure proportional to the number of molecules above any one point. The pressure thus increases as we descend in the atmosphere, just as in liquids; or viewed from the surface, pressure decreases as we go aloft, so that for every increase of 18,000 feet, the pressure is about one-half its former value. Because air, unlike water, is compressible, a rapid decrease in pressure occurs at low altitudes, about 34 mb per 1,000 feet or 1 inch of mercury (see table II); but above a few thousand feet the pressure decreases at a much slower rate.

b. Just as the pressure on the surface varies from point to point, so does the pressure aloft vary from point to point at the same level, and, also, since the standard atmospheric pressure was defined, we must define an average pressure condition aloft. Starting with the standard sea level pressure at a temperature of 59° F., the average condition assumes a mean lapse or decrease in temperature of 3.57° F. per 1,000 feet, and the following tables may then be computed.

TABLE II.—*Standard pressures at 1,000-foot levels*

Feet	Inches of mercury	Feet	Inches of mercury
18,000-----	14. 94	8,000-----	22. 22
17,000-----	15. 56	7,000-----	23. 09
16,000-----	16. 21	6,000-----	23. 98
15,000-----	16. 88	5,000-----	24. 89
14,000-----	17. 57	4,000-----	25. 84
13,000-----	18. 29	3,000-----	26. 81
12,000-----	19. 03	2,000-----	27. 82
11,000-----	19. 79	1,000-----	28. 86
10,000-----	20. 58	Sea level-----	29. 92
9,000-----	21. 38		

TABLE III.—*Vertical relation of 100-millibar levels*

Millibars	Feet	Meters	Millibars	Feet	Meters
400-----	24, 370	7, 425	800-----	6, 200	1, 889
500-----	18, 520	5, 643	900-----	3, 112	948
600-----	13, 740	4, 186	1, 000-----	348	106
700-----	9, 700	2, 955	1, 013-----	Sea level	Sea level

c. It should be borne in mind that these tables represent average conditions, and that any altimeter (essentially a barometer) may be in error, high or low, depending upon the local departure from average.

35. Isobars.—*a.* This local departure from the average is one of the phenomena that the weather forecaster utilizes constantly. The pressure at a number of stations is entered upon a map called a synoptic chart, and the weather is analyzed from these pressures. If some of the stations are in the mountains and others near sea level, the upper stations will report a lower pressure. A common level or altitude must be chosen which is sea level. The weather observer, therefore, must correct his observed pressure by adding to it the pressure exerted by an imaginary column of air between the level of his station and sea level.

b. Once the corrected pressures are received and recorded, the forecaster can draw isobars or lines joining points on the map having the same pressure. The Army requires that isobars be drawn for intervals of three millibars for all recorded pressures divisible by 3. Thus isobars would be drawn for pressures of 996, 999, 1,002, 1,005 mb., etc. Figure 30 is a part of a map with a number of isobars drawn. Beginning at the left, we know the 1,002 isobar must lie between the pressures recorded as 1,002.2 and 999.8 and be much closer to the former. Note that these lines are drawn smoothly, but do bend rather

sharply along the dotted axis. Except for bends along such fronts, isobars are continuous and gently bending, eventually closing upon each other again, just as the 999 and 1,002 do, and the 1,008 would do if carried above the limit of the chart. No isobar may branch out in a Y or fork, and separate isobars may not cross.

36. Pressure gradient and wind.—When the forecaster has

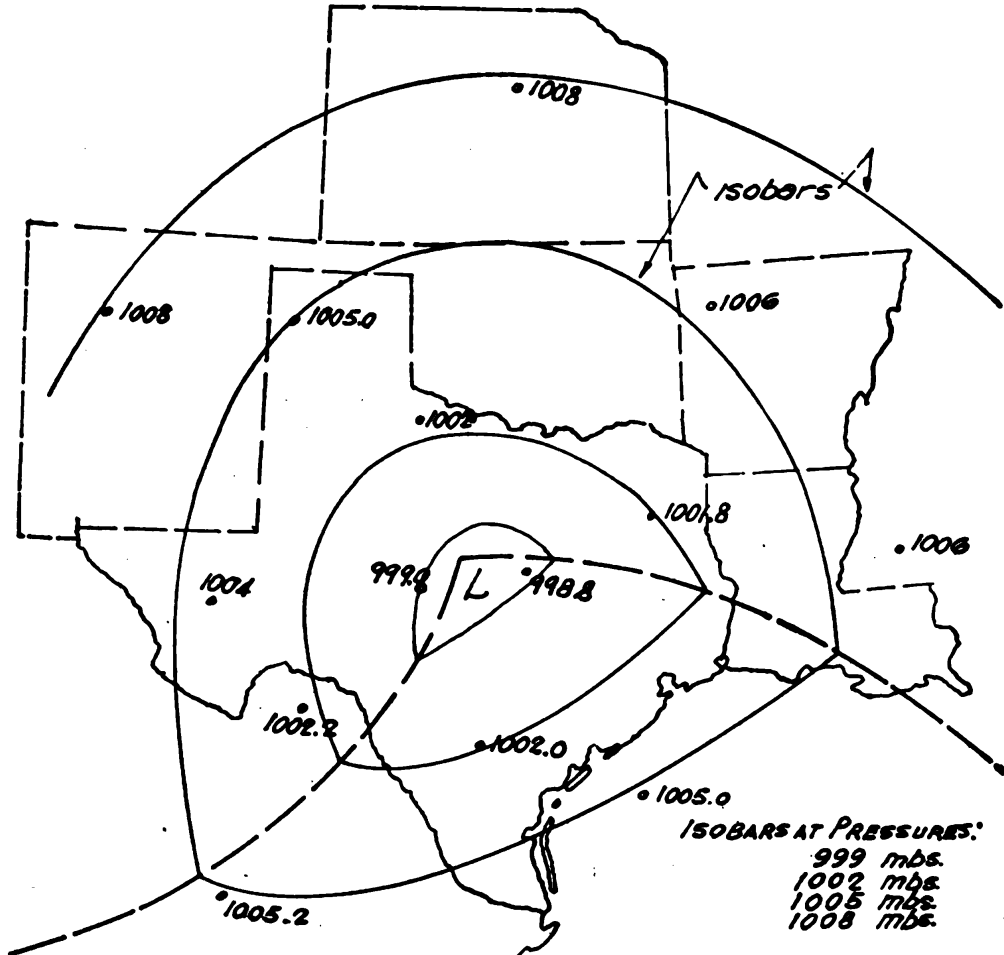


FIGURE 30.—Pressure field around a low pressure center as shown by isobars.

drawn all the isobars, he has a quickly grasped picture of the pressure variations, or pressure field. The lines are quite similar to contour lines upon a map, and not only show the mountains and valleys or centers of low and high pressure but also give an idea of the steepness of the hill, or the pressure gradient. The latter is defined as the ratio of the change in pressure to the distance between points. A large change in pressure within a small distance would indicate a large pressure gradient, and the isobars would crowd closely together. High pressure gradients are especially watched for, because associated with such regions are high winds blowing approximately parallel to the

isobars. A pilot or forecaster has a good idea of the wind speed and direction from a quick look at the isobars upon the synoptic chart, for wind speed is proportional to pressure gradient. The synoptic chart has many other features, too, which are required for a complete grasp of the weather along a route or at a station and which will be taken up later.

37. Mercurial barometers.—*a.* Thus far we have considered the phenomena associated with pressure but have not dealt with methods

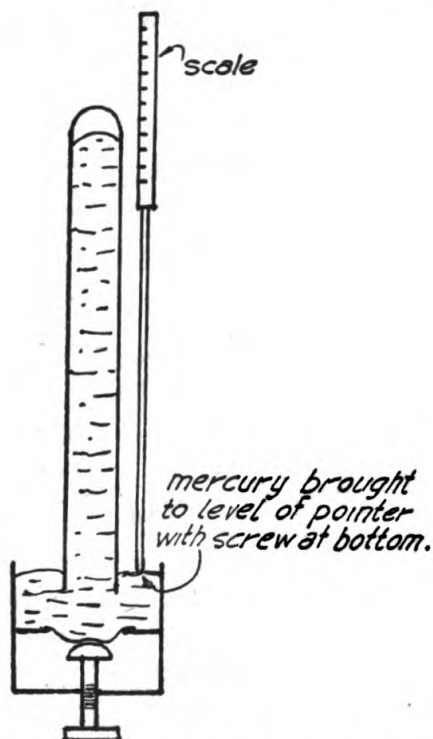


FIGURE 31.—Principle of Fortin type barometer.

of precisely measuring pressure. A working knowledge of such instruments is useful, and absolutely essential in the case of altimeters.

b. Present-day mercurial barometers differ little in principle from Torricelli's tube. The tube is a glass cylinder filled with mercury evacuated at the top. A brass measuring scale is fixed to the glass and is used with a sliding vernier for accurate readings.

There are two common mercurial barometers in use, namely, the Fortin and the Kew. The Fortin barometer has a leather pouch at the bottom of the column by means of which the height of the outside mercury may always be brought to a fixed point so that the scale will read the true height of the mercury column. No such adjustment is possible in the Kew barometer, consequently, an extra source of error

is introduced which must be corrected. Other corrections must be made for temperature, gravity, and latitude.

38. Aneroid barometers.—*a.* The other type of barometer in common use, the aneroid, depends upon the movement of a hollow corrugated metal box under varying pressures. The inside is airtight and evacuated, so that pressure is exerted only by the outside air against a spring inside that prevents collapse of the bellows. When the atmospheric pressure increases, it squeezes the sides closer together, and this movement is multiplied by suitable levers and indicated upon a calibrated scale. The scale may be calibrated in inches of mercury, in millibars, or possibly in feet or meters corresponding to the standard pressures (see tables II and III). When calibrated in feet or meters, the aneroid barometer serves as an altimeter. If a pen replaces the pointer and is allowed to trace a line on a rotating drum, a continuous record of pressure is obtained. Such an instrument is called a barograph.

b. Both the mercurial and aneroid barometers are necessary for the different requirements of the pilot and the Weather Service. Wherever precise measurements are necessary, the mercurial type must be used. The reading of a mercury barometer is much more difficult than a glance at an aneroid dial, and corrections for the former require more time than a pilot can spare. For all these reasons the aneroid has become increasingly refined until it approaches the mercurial barometer in accuracy.

c. The necessity for an adjustable dial upon an altimeter arises because of local variations in pressure. The pointer is so adjusted as to indicate pressures corresponding to the altitudes resulting from the standard atmosphere; however, the actual state of the atmosphere seldom corresponds to the standard. Therefore, the dial is moved under the pointer until the actual pressure will cause the altimeter to read the true height at that field. For instance, if at the time a plane took off from Corpus Christi the sea level pressure was found to be 30.22'', the pointer would indicate the plane was 300' below sea level because of the high pressure at that station, an increase of 0.30'' corresponding to 300'. If the pilot adjusts the zero mark of altimeter setting to 30.22'', by effectively rotating the dial, it will read zero at take-off. If now he flies to Hensley Field, Dallas, which reports a pressure, reduced to sea level, of 29.82'', the pressure will be reduced upon his altimeter and will consequently read high by 400'. If he tries to land blind with this setting, disaster may result. Therefore, if the altimeter is reset to be 29.82'', it will read the true height of the station when he lands. A good habit to form is to reset the altimeter all along the route.

39. Pilot balloon ascensions and upper winds.—When a pilot is navigating it is important for him to have a close estimation of the winds that exist aloft. The direction and velocity of the upper winds are determined by the movement of ascending balloons. These rubber balloons are filled with hydrogen and will rise at a known rate. Thus the height of the balloon at any time is known. The change in position of the balloon gives the data for determining the direction and velocity of the winds at any level. Also, the direction and velocity of the winds may be estimated by watching the movement of the clouds.

PROBLEMS

1. A man exerts a 50-pound pull upon a hydraulic jack. The driving piston is 1 inch in diameter and the lifting piston 3 inches. How heavy a weight can the jack lift?

2. If the driving piston in problem 1 moves $\frac{1}{2}$ inch each stroke, how many strokes are necessary to raise a flat tire clear off the ground if it is 6 inches from the rim to the outside tread of the tire when inflated? Neglect the thickness of the rubber.

3. How heavy a man could be supported upon a pine raft 4 feet on a side and 4 inches thick? Pine weighs 30 pounds per cubic foot and water 62.4 pounds per cubic foot.

4. How much equipment could the man in problem 3 carry if the raft had been made of balsa weighing 10 pounds per cubic foot?

5. The height of a mercurial barometer on the surface is observed to read 29.95 inches. What would the barometer read 750 feet above the station?

6. If a balloon ascends at 6 feet per second and disappears in the clouds in 8 minutes, how high are these clouds?

SECTION VII

WORK AND ENERGY

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40. Definition of work and energy.—*a. Work.*—(1) When a cadet stands in ranks with a rifle on his shoulder, he does not become very fatigued. However, let him begin to do rifle calisthenics, and

perspiration and aching muscles will give ample testimony of the labor required to perform the rifle drill.

(2) This illustrates the difference between doing work and merely exerting force. Work involves not only the exertion of force but action that is making something move. Pushing or pulling on a hangar is not doing work on the hangar. A force that keeps itself up without any motion in the direction of the force does not involve the doing of work. For example, a chair may support a sitting man and exert a force thereby, but no work is being done by the chair.

(3) What we call work may be considered as a physical quantity proportional to each of two factors: the amount of force acting; and the amount of movement or displacement in the direction in which the force acts.

(4) A body may be moving, and may be acted upon at the same time by a force, yet without any work being done; for example, a stone whirled around at the end of a string. The stone is acted upon by a force pulling through the string, toward the center of the circle. Since there is no displacement toward the center, there is no displacement in the direction of the force, so there is no work being done by simply holding the string. The amount of work done, when a force is exerted and there is at the same time a displacement in the direction of the force, is the product of that force by the displacement. This is expressed by $w=fd$, in which w is work done, f is the force, and d is the displacement, or distance over which the force operates. If the force is not constant during the displacement, then we must use the average force.

(5) Work units are simple and natural. Just combine the unit of force with the units of displacement or distance. A foot-pound is the work done when the exertion of 1 pound of force is accompanied by a displacement of 1 foot in the direction of that force. If a Springfield rifle weighs 9 pounds and is lifted 4 feet off the ground, the work done is 9×4 or 36 foot-pounds.

(6) Any combination of a force unit with a length unit might be selected as a unit of work. Only a few are generally used. The most common unit in the English system is the foot-pound. In the metric system there is the dyne centimeter. This is the absolute unit of work used in almost all theoretical discussions. The expression "dyne centimeter" is so awkward that the unit has been given a name of its own, the erg. Of course, the amount of work represented by an erg is very small; when you turn your hand over, thousands of ergs of work are done. A more convenient multiple of this unit, the joule, is often used. A joule is defined as 10 million (10^7) ergs.

(7) A joule is equal to 0.74 foot pounds; a foot-pound equals 1.35 joules.

b. Energy.—The fact that a cadet can lift a rifle off the ground indicates that he has ability to do work. This ability to do work is called energy. Its amount is the same as the amount of work it will do, and is expressed in the same units as work, i. e., foot-pounds, ergs, etc. The term work is applied to energy only during the process of transfer of energy.

41. Power.—*a.* When a cadet drills in double time, he is drilling at a rate greater than usual. He is doing the same amount of work in half the time. The rate of doing work is called power. Power is the rate at which work is done or the amount of work done per unit of time.

$$P = \frac{w}{t}$$

The unit by which power is measured must be a unit of work per unit of time. The absolute unit of power in the metric system is the erg per second; but, since this unit is too small for convenient practical use, it is customary to employ the watt, which is defined as one joule per second. The kilowatt, or 1,000 watts, is more convenient than the watt when measuring large amounts of power. The kilowatt hour is a unit of energy (not of electricity). It is the amount of energy transferred in 1 hour to any agency (as a motor) that is consuming 1 kilowatt of power. In paying the electric bill at so much per kilowatt hour, you do not pay for a quantity of electricity, but for work done, that is, for energy supplied.

b. The common unit of power in the English system of measurement is the horsepower (hp), based originally on measurements made by James Watt on the work rate of horses. It is now standardized at the arbitrary value of 550 foot-pounds of work per second.

c. One horsepower is equivalent to about 746 watts, or roughly $\frac{3}{4}$ kilowatt, so that a 750-kilowatt dynamo would require a 1,000-horsepower engine to drive it. One kilowatt hour equals 2.66×10^6 foot-pounds of work.

Example: A force of 9,800 dynes acts for 10 seconds and pushes a body 1 meter. How much work is done?

$$\begin{aligned} w &= f \times d = 9,800 \times 100 \text{ dyne centimeters or ergs} \\ &= 980,000 \text{ ergs} \\ &= 1,000 \text{ gram centimeters} \\ &= 1 \text{ kilogram centimeter} \\ &= .098 \text{ joule} \\ &= .098 \text{ watt second.} \end{aligned}$$

At what power is the above amount of work done?

$$P = \frac{w}{t} = \frac{.098}{10} = .0098 \text{ watt}$$

as one horsepower is 746 watts:

$$\text{hp} = \frac{.0098}{746} = .0000132 \text{ horsepower}$$

If this work is done by an electric motor at 100 percent efficiency, what will be the cost at 10 cents per kilowatt hour?

.098 watt second is $\frac{.098}{1000}$ kilowatt second, or $\frac{.000098}{60 \times 60}$ kilowatt hour costing 0.000000272 cent.

42. Kinetic energy.—*a.* Energy has been defined as the ability to do work. The energy contained by a body in motion is called kinetic energy. Before a moving body can be brought to rest, a force must be applied and this force will move for some finite distance, doing a definite amount of work in the process. If a body of mass M grams has a velocity of V centimeters per second, it contains a definite amount of kinetic energy. If a force F applied for a distance D will bring the body to rest, the ability of the body to do work may be expressed as $F \times D$. From our formulas for accelerated motion,

$$V^2 = 2AD \text{ (} A \text{ is acceleration in centimeters per second).}$$

If both sides are multiplied by $\frac{M}{2}$:

$$\frac{MV^2}{2} = MAD$$

but force F is equal to the mass times the acceleration, or

$$\frac{MV^2}{2} = FD = KE = \frac{MV^2}{2}$$

which is the amount of work obtainable in bringing the body to rest. In this derivation, forces were expressed in dynes and distances in centimeters; so the expression $MV^2/2$ will be the kinetic energy in ergs of a body of mass M grams and moving with a velocity of V centimeters per second. A body in motion is able to do an amount of work equal to its kinetic energy; and conversely, if a certain amount of work is done accelerating a body, it will obtain a kinetic energy of this amount. So, if the only resistance is that due to inertia, the kinetic energy of translation imparted to a body by the action of a force is equal to the work done upon it. Thus we can calculate the

kinetic energy of a body at any instant without having any knowledge of the forces which produced the motion or of the previous history of the body, provided we know its mass and speed at the instant in question.

b. Since the kinetic energy of a body depends on the square of the magnitude of the velocity and not on direction, it is a scalar quantity. It is a quantity equivalent to work and is measured in the same units as work.

43. Potential energy.—*a.* Besides kinetic energy, which manifests itself by movement, we are familiar with bodies which have energy because of their position with reference to other bodies or because of the relative positions of their parts. For example, a coiled spring has potential energy. Another example is potential energy of height. In a waterfall, the potential energy of the water at the top may be converted into mechanical energy as it loses elevation and passes through a turbine. Other examples, the nature of which is less obvious, are the energy apparently stored in coal or other fuel which is made available by combustion, and the energy in a battery or in a stick of dynamite. In none of these cases is any motion apparent after the energy is once stored. Energy existing in an apparently inactive or latent form is usually called potential energy.

b. It is evident that energy can pass from the potential to the kinetic form and back again. When a pendulum swings, for example, the pendulum bob rises to a certain level and stops, its energy being all potential; it then begins to descend, and as it loses potential energy, it gains speed and kinetic energy until at the lowest point of the swing it has its greatest kinetic and its least potential energy. The process is now reversed until the motion again stops and the energy is again all potential. A vibrating piano string and the waves of the ocean also illustrate this transformation. Potential energy is measured the same way work is measured. That is, the ability of a body to perform work is initially measured by the amount of work it does. Work is equal to force times distance. If a monkey wrench were dropped from an airplane at 5,000 feet, gravity would exert a force of 1 pound for 5,000 feet of distance, doing $5,000 \times 1$ foot pounds of work. The wrench will, just before it strikes the ground, have converted 5,000 foot pounds of potential energy into 5,000 foot pounds of kinetic energy. When it collides with the ground, this energy will be dissipated as heat.

c. When you get a flat tire on your car and start pumping the tire up, you do work on the pump. The pump compresses the air, and the air is forced into the tire until it can support the weight of the car.

d. When your tire blows out, the air in the tire which was compressed to 30 pounds per square inch does work and reduces itself to the same pressure level as the air outside, i. e., to a pressure or force of about 15 pounds per square inch. In reducing its pressure, the air expands and increases in volume. When the tire blows out, this energy is all soon dissipated as heat to the atmosphere, but it could have been made valuable if used to drive a compressed air motor.

44. Conservation of energy.—a. Next to the concept of energy itself and the reality of its existence, the most important principle connected with this subject is stated thus: *The total amount of energy in the universe remains constant.*

b. It cannot be asserted that we absolutely know this, but the more information there is gained about physical and chemical processes, and the better their nature is understood, the stronger the evidence becomes that the principle is universally true. This principle of the conservation of energy is regarded as a cornerstone of physics.

c. If a man does a thousand foot-pounds of work, turning the crank of a derrick, exactly that amount of energy will appear in the way of raising the weight, hauling up the blocks and chains, heating the bearings and pulleys, and filling the air with squeaks. Every erg of energy can be accounted for. Some of this energy supplied to the crank appears as potential energy of height as the weight is lifted, but a considerable percentage will be lost in the form of heat from friction. The heat generated in this way will be another form of energy but quite useless as far as man is concerned. There is a definite relationship between the amount of mechanical energy lost and the amount of heat energy that appears. This relationship is spoken of as the mechanical equivalent of heat; 4.19 joules of mechanical energy will produce 1 calorie of heat energy.

Example: If a 30-gram bullet moving 1,000 meters per second is imbedded in a block of wood, how many calories of heat energy will appear?

Solution: The kinetic energy of the bullet will all appear as heat energy:

$$KE = \frac{MV^2}{2}$$

V is 100,000 centimeters per second

M is 30

$KE = 15 \times 10^{10}$ ergs or 15×10^3 joules

15,000 joules = 3,580 calories

45. Friction.—*a.* Friction is the resistance to the relative motion of one body sliding over another. This resistance naturally requires that work be used to overcome it, and this work is dissipated in the form of heat. If two bodies are rubbing together without lubrication, the resistance of friction is directly proportional to the force holding them together. The area of contact has very little to do with the resistance. Suppose that a block of wood weighing 10 pounds is resting on a plate of glass. In order to move this wood over the glass it is found that a force of 2 pounds must be exerted. In this case two-tenths of the force between the bodies must be exerted to overcome friction. This ratio is called the coefficient of friction. It is different for different conditions. If the force holding the two bodies together is designated as F , the coefficient of friction as C , and the resistive force as R :

$$R = CF \text{ or } C = \frac{R}{F}$$

As an example, the coefficient of friction of iron on iron is .25. Therefore, since there is no relative sliding motion of a moving wheel on a rail, a locomotive will be able to exert a draw-bar pull of 25 percent of its weight on the drive wheels. If the locomotive tries to pull with a greater force, the wheels will slip.

Example: The coefficient of friction between wood and concrete is about .4. How much work is done by a man in pushing a box weighing 175 pounds for a distance of 20 feet along a sidewalk?

Solution:

$$\text{Force} = .4 \times 175 = 70 \text{ pounds}$$

$$\text{Work} = F \times D = 70 \times 20 = 1,400 \text{ foot pounds}$$

When a body moves through air there is a certain resistance to the movement which may be considered a type of friction. This resistance increases as the speed and size of the body increase, and decreases as the density of the air decreases. An example of this is the pilot balloon used by weather stations to measure winds aloft. The accuracy of this measurement depends on a constant rate of ascent of the balloon. As the balloon rises it expands under the reduced pressure at higher elevations. This would slow the balloon in its ascent except that the density of the air decreases and the balloon continues to rise at an approximately constant rate of speed.

b. Another example of the effect of air viscosity may be mentioned. When raindrops form and grow in size, they fall with an increasing velocity which is greater for large drops than for small drops.

Extremely fine droplets which are found in clouds and fog do not seem to settle at all, and may remain suspended in the air almost indefinitely. The increased speed with increased size may be easily understood if one considers the increase in surface area (and area for air friction to act upon) when a large drop is broken up into many small droplets. There is a maximum limit to the size to which rain drops may grow and consequently a limit to the speed with which they may fall. If a drop grows beyond this size, the forces within the drop set up by its passage through the air cause a splitting of the drop into two or more smaller drops. These falling drops do not, as usually assumed, take on a tear drop shape but instead remain almost spherical, being flattened slightly in a vertical direction.

QUESTIONS AND PROBLEMS

1. When a ball player catches a baseball, does the man or the ball do work as the ball is stopped?

2. If a ball weighing 50 grams and traveling 30 meters per second is stopped, how much work is done? Explain the amount of work in ergs, joules, and kilowatt hours.

3. If a 50-pound bomb is dropped from an airplane at 20,000 feet, how much potential and how much kinetic energy does the bomb have at 20,000 feet, 15,000 feet, and at the ground just before striking? (Neglect the chemical energy of the explosive. Neglect air friction.)

4. How much power is required to accelerate a 2,000-kilogram (about 4,400 pounds) car from 14 meters per second (about 30 mph) to 28 meters per second (about 60 mph) in 20 seconds? (Neglect friction and wind resistance.)

5. How much horsepower is used for lifting if an airplane weighing 2,000 kilograms climbs 1,000 meters (about 3,000 feet) in 60 seconds? Assume no change in speed and neglect air resistance.

6. If an automobile loses one-half of its velocity in $\frac{1}{4}$ mile of coasting, what fraction of its kinetic energy has been transformed into heat?

7. A pendulum bob in swinging lifts $\frac{1}{2}$ inch at the outer limits of its stroke. If the bob weighs 1 kilogram, what is the potential energy at the end of the stroke? At the center? What is the kinetic energy at these points?

8. How many calories of heat energy will appear in the bearings of the pendulum in problem 7 if friction brings it to a halt?

9. How many calories of energy are given off by a 100-watt light bulb in 1 hour? How much horsepower of electrical energy is being consumed?

SECTION VIII

FLUIDS IN MOTION

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46. Velocity of fluids.—In section VI we studied the properties of fluids at rest. Now that we have developed expressions for the energy of any body, we can apply these formulas to the study of the flow of fluids or hydrodynamics.

a. Complete calculation of the properties of flow of fluids is very complicated. In cases dealing with incompressible fluids or with compressible fluids (gases) remaining at the same density during the flow, the calculation is much simplified. In this section we shall always assume for purposes of simplification that the fluids have constant density. If the fluid is air, the results of this calculation will be only an approximation but for our purposes will be sufficiently accurate.

b. If there is a steady state of motion (that is, the present motion has remained the same for some finite period of time and will remain the same for some finite time to come), the amount of fluid entering some definite space must be the same as the amount of fluid leaving that same space in a unit time. If we consider the fluid as incompressible, we may say also that the volume of the fluid entering must equal the volume leaving. Consider the fluid flowing through the reducer pipe in figure 32. If some definite volume V_0 enters the large end, the same volume V_0 must leave the small end in the same period of time. If the fluid were compressible, and with the differences in pressure that would exist at the two points, the volumes of fluid entering and leaving would not be the same, but the mass or weight of fluid in each case would be equal. We assume here and in the rest of our calculations that the fluid is incompressible. It is easy to see that the fluid will have to move faster through the small end than through the large end. If in the large end a part of the fluid moves in one second from point P_1 to point P_2 , a part of the fluid in the small end will have to move a longer distance from P_3 to P_4 so that the volume of fluid between cross sections P_3 and P_4 will be equal to that between P_1 and P_2 .

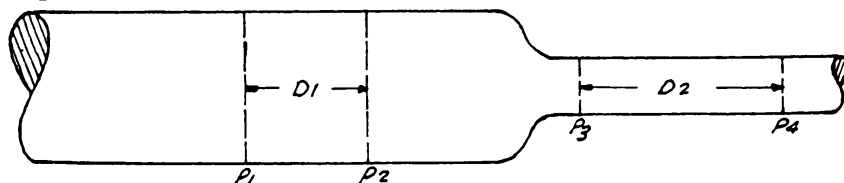


FIGURE 32.—Pipe reducer showing increase of velocity with decreased size pipe.

D_1 and D_2 will be the distance traveled in one second at each point; and as velocity is defined as the distance traveled in 1 second, $D_1 = V_1$ and $D_2 = V_2$ where V_1 and V_2 are the velocities of the fluid at these points. The volume in each case will be equal to the cross sectional area of the pipe times the distance D (or V), and we may set up an equation for velocities of flow in pipes:

$$A_1 V_1 = A_2 V_2$$

(A_1 and A_2 are cross section areas; V_1 and V_2 are velocities of motion.)

Example: Air flows through a carburetor with a venturi constric-

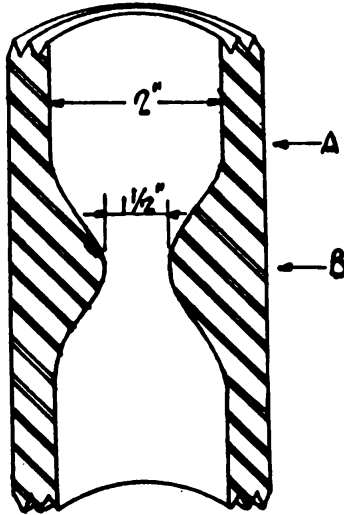


FIGURE 33.—Venturi constriction in pipe.

tion as in figure 33. If 10 cubic feet of air per second enter the tube, what will be the velocities of the air at point A and at point B ?

Solution: The cross section area at point A is:

$$\left(\frac{1}{12}\right)^2 (3.141) = .0218 \text{ square feet.}$$

The cross section area at point B is:

$$\left(\frac{.75}{12}\right)^2 (3.141) = .0126 \text{ square feet.}$$

$$V_a = \frac{\text{Volume}}{\text{Area}} = \frac{10}{.0218} = 460 \text{ feet per second}$$

$$V_b = \frac{10}{.0126} = 794 \text{ feet per second.}$$

47. Energies of fluids in motion.—The present basis for all calculations of fluids in motion, or hydrodynamics, is the work of Bernoulli. The principle of his work is simple: The total energy carried and transmitted by any fluid will be the same at any point in its path. One type of energy may be transmitted to another, but the total will be constant if no energy is added from the outside as by a pump. If we assume that there is no friction converting mechanical energy into heat energy and that the fluid is incompressible, the only types of energy with which we will be concerned are those listed in the following paragraphs:

a. Potential energy of height.—A unit mass (1 gram) of fluid will have a potential energy proportional to its height and the force of gravity or $g \times H$ where g is 980 (gravity exerts about 980 dynes of force on 1

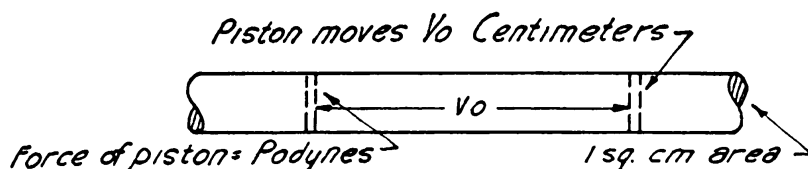


FIGURE 34.—Pressure energy of flow.

gram of mass) and H is the height in centimeters above some reference level. The product $g \times H$ will give this energy in ergs per gram of fluid.

b. Kinetic energy due to velocity.—For an amount of fluid of mass M , this energy will be $MV^2/2$, or for a unit mass of 1 gram it will be simply $V^2/2$ ergs when the velocity is expressed in centimeters per second.

c. Pressure energy of flow.—Imagine 1 gram of fluid having a volume V_0 flowing in a pipe shown above which has a cross section area of 1 square centimeter. A volume of V_0 cubic centimeters flowing through will push an imaginary piston a distance V_0 centimeters; and if the fluid has a pressure of P_0 dynes per square centimeter, the work done by this moving fluid will be $P_0 V_0$ ergs. This energy would be the same if the same volume of fluid were passing through a larger size pipe at a smaller velocity, as may be seen by considering that the force on the imaginary piston will be greater for the same pressure but the distance traveled will be less.

d. Sum of these energies, constant.—If we can determine the sum of these energies at any point in the flow, we may say that this sum will be constant for any other point in that path of the flow.

$$\text{Total energy} = g \times H + \frac{V^2}{2} + P_0 V_0$$

(V is velocity and V_0 is volume of 1 gram of fluid.)

As this expression is for each gram of fluid, V_0 must have a value of $1/d$ where d is the density of the fluid; hence we may simplify the equation as follows:

$$\text{Total energy} = g \times H + \frac{V^2}{2} + \frac{P}{d}$$

(g is 980; H is in cm; V is in cm per second; P is in dynes per square centimeter; and d is in grams per cubic centimeter.)

If the values of height, velocity, and pressure are known at one point, an equation may be set up as follows (known values at point 1 have subscript 1 and unknown values at point 2 have subscript 2):

$$(gH_1) + \frac{(V_1)^2}{2} + \frac{P_1}{d} = (gH_2) + \frac{(V_2)^2}{2} + \frac{P_2}{d}$$

48. Illustrations and applications.—*a.* Take the case of the fluid flowing through the pipe in figure 32. The terms for height on each side of the equation will be the same and will cancel. The velocity will be smaller in the large end than in the small end; therefore, for the equation to balance, the pressure must be less in the small end than in the large end.

Example: If the large end of the pipe in figure 32 has a diameter of 4 centimeters, and the small end a diameter of 2 centimeters, and passes 3 liters of water per second; what will be the difference in pressure between the two ends of the pipe?

Solution:

$$V_1 = \frac{3,000}{(2)^2 \pi} = 238 \text{ cm per second}$$

$$V_2 = \frac{3,000}{\pi} = 952 \text{ cm per second}$$

$$\frac{(V_1)^2}{2} + \frac{P_1}{d} = \frac{(V_2)^2}{2} + \frac{P_2}{d} \text{ or}$$

$$P_1 - P_2 = \frac{(V_2^2 - V_1^2)d}{2} = \frac{910000 - 56500}{2} = 427,000 \text{ dynes per square centimeter less in the small end.}$$

b. In a waterfall the pressure will be approximately the same at the top as at the bottom; the pressure terms will cancel. The potential energy will decrease during the fall, but the kinetic energy will increase, indicating an increased velocity as expected.

Example: The stream velocity at the top of a fall is 1 meter per second. If the falls are 30 meters high, what will be the velocity of the water when it reaches the bottom?

Solution:

$$V_1 = 100 \text{ cm per second}$$

$$h_1 = 3,000 \text{ cm}$$

$$h_2 = 0$$

$$gh_1 + \frac{V_1^2}{2} = gh_2 + \frac{V_2^2}{2}$$

$$980 (3,000) + \frac{10000}{2} = \frac{0 + V_2^2}{2}$$

$$V_2 = \sqrt{5,880,000 + 10,000} = 2,420 \text{ cm per second} = 24.20 \text{ meters per second.}$$

c. Several applications of the Bernoulli principle are well known. The Venturi tube in a carburetor uses this principle for injecting the gasoline into the air stream. At the point of maximum constriction, the velocity of the air is highest and the pressure is reduced below that of the outside air, forcing the gasoline through the injection tube.

d. The Pitot tube on the outside of an airplane is used for measuring air speed, and the above principle applies in its use. In use, the tube is pointed into the wind or straight ahead on an airplane. The air blows rapidly by point A with approximately the speed of the

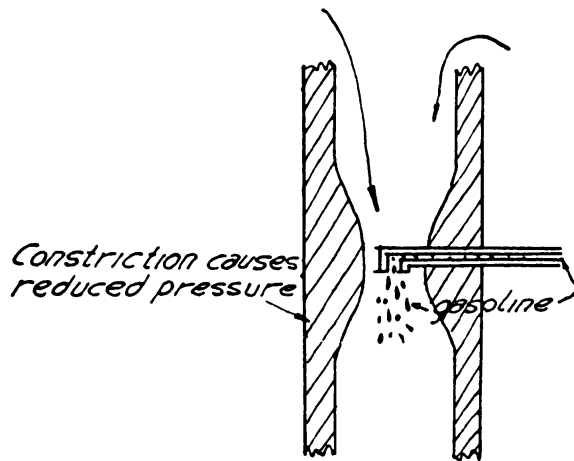


FIGURE 35.—Schematic picture showing principle of carburetor.

airplane and at point B the air is carried along with the tube. In the simplified case, assume that the tube stands still and the air is blowing by with a speed that we wish to determine. At point A the air has now high velocity and at point B we have zero velocity. The equation relating velocity to pressure is:

$$\frac{Va^2}{2} + \frac{Pa}{d} = \frac{Vb^2}{2} + \frac{Ph}{d}$$

In this equation the potential terms have been omitted, as there is no change in elevation. V_b will be zero and V_a will be the velocity of the plane. Solving for V_a the equation reduces to:

$$V_a = \sqrt{\frac{2(P_b - P_a)}{d}}$$

The air speed indicator in an airplane is a sensitive pressure measuring device which measures the difference between the two openings and which has a scale so calibrated that it will read directly in miles per hour. At high altitudes the density of the air is reduced and consequently the air speed indicator will ordinarily indicate a lower speed than the plane is actually traveling.

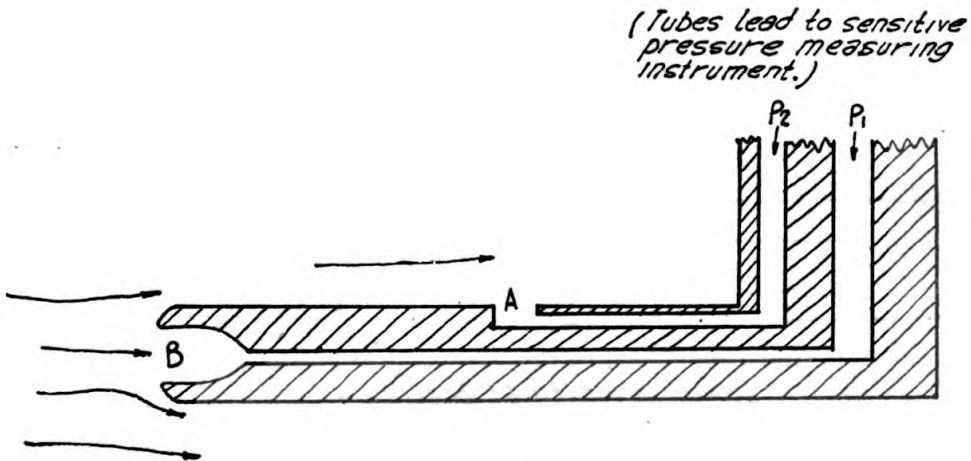


FIGURE 36.—Schematic section of Pitot tube.

Example: If the pressure difference between the two openings on a Pitot tube is 20 millibars (1 millibar is 1,000 dynes per square cm.), how fast is the airplane traveling? Assume an air density of 0.0013 grams per cubic centimeter.

Solution:

$$\begin{aligned} V_a &= \sqrt{\frac{2(P_b - P_a)}{d}} \\ &= \sqrt{\frac{2(20) \times (1000)}{.0013}} \\ &= \sqrt{30,800,000} \\ &= 5,550 \text{ centimeters per second} \\ &= 55 \text{ meters per second} \\ &= 198 \text{ kilometers per hour} \end{aligned}$$

e. The lift of a modern wing is developed upon the application of the Bernoulli principle. Air is made to travel a longer path over the top of the airfoil than over the bottom. Since the air on the top has farther to travel its velocity is greater, and therefore the pressure is less on the top than on the bottom. Hence there is an induced lift because of the flow of air.

49. Icing.—There is one dangerous consequence of the rapid flow of air. This is in the carburetor. In paragraph 46 we saw that the pressure at the throat of the carburetor is but a fraction of that at the entrance. The consequent lowering of temperature is extremely marked. At air temperatures between 70° and 80° F. the air will cool to the freezing point at the throat; the moisture in this air will then freeze and clog the carburetor. Since it takes several minutes for the metal surface of the throat to cool off, this icing is not always detected

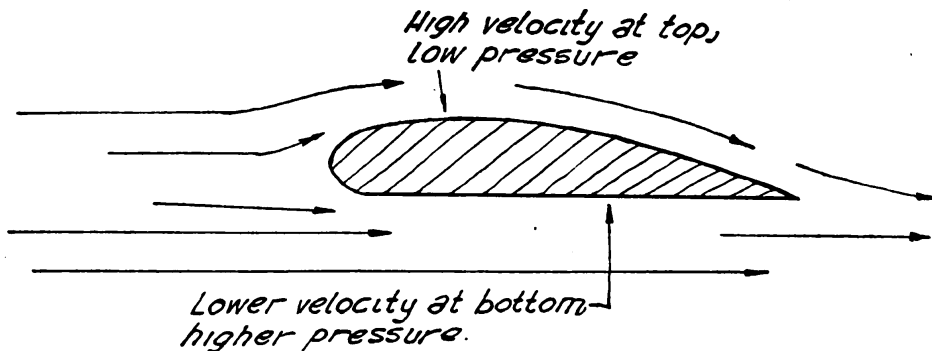


FIGURE 37.—Flow of air over an airfoil.

in the warm-up, and the throat will clog just about the time the pilot starts to climb steeply on the take-off. Many pilots are dead because they overlooked this simple little fact. Today we employ carburetor preheaters, but the pilot still must know when to use them and when not to.

QUESTIONS AND PROBLEMS

1. Considering the requirements for accelerated motion, give a simple explanation why the pressure is reduced at a constriction in a pipe carrying running water.
2. Cold air is denser than warm air. Will the air speed indicator give high, low, or correct reading in very cold weather if the instrument is not corrected for temperature?
3. If the wind blows up a steep-sided valley that becomes narrower at the upper end, what will be the maximum wind velocity if the valley is 3 times as wide at the mouth as at the top and the entering wind 20 miles per hour?

4. If water from a fall is diverted down a pipe for providing water power, what is the pressure in dynes per square centimeter if there are 40 meters of head? Assume that there is no flow.

5. If the water in the above fall is delivered to a turbine through a pipe of 20 centimeters radius and 2 cubic meters of water are delivered per second, what is the pressure at the bottom of this pipe?

6. What will be the difference in pressure between the static and dynamic pressure tubes for the air speed indicator if the airplane is traveling 400 kilometers per hour?

SECTION IX

TEMPERATURE AND HEAT

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50. Nature of temperature.—We are familiar with the sensations that bodies produce when they are hot or cold. While these are unreliable except as rough indicators, they furnish us on the whole with a fairly consistent system of temperature ranges in good agreement with other observations on the effects of heat. We observe that an object which feels hot can always be made to show its heat in other ways also. For instance, a metal rod is a little longer when hot than when cold; a quantity of gas exerts a greater pressure when heated than before; etc.

51. Definition of heat.—*a.* The supply of heat cannot be weighed; therefore it cannot be a substance (as at one time was thought), but must be related in some way to motion.

b. When heat is applied to a body, it increases the energy of that body; and since no change can be detected in either the kinetic or the potential energy of the body as a whole, it appears that the energy must have been given to the molecules of which the body is made. Molecules are known to possess both kinetic and potential energy. This is true for the molecules which have been expanded by heat, for work must have been done upon the molecules to separate them in opposition to the forces of cohesion. Heat is a form of energy which in gases is practically the kinetic energy of molecules, and which in solids and liquids also includes potential energy due to expansion.

c. When a gas is confined to a vessel and the vessel is heated, the gas molecules striking the heated side of the vessel in their incessant motion rebound with greater speeds. These molecules then strike others, and so on until the entire gas is heated. When one end of a metal rod is placed in a fire, the entire rod becomes warmer as the heat is gradually conducted along it. The kinetic theory of matter explains this phenomenon as the result of the progressive transference of molecular kinetic energy from one molecule to another throughout the rod.

52. Definition of temperature.—*a.* The application of heat to a body usually causes an increase in its temperature. The term *temperature* is used to express how cold or how hot an object is; *cold* implies a low temperature and *hot* implies a high temperature with reference to the surroundings. A more definite idea of temperature can be realized by considering what occurs when a hot body is brought into contact with a cold one; for example, a hot steel rod plunged into cold oil. The rod becomes cooler and the oil warmer, an indication that the hot body gives up some of its energy to the cold one. This process continues until a state of thermal equilibrium is reached, and this condition signifies that the same temperature prevails throughout. Consequently, temperature is that property of a substance which determines whether heat will flow from it or toward it when it is placed in contact with some other body.

b. Terms such as *hot*, *cold*, *warm*, and *cool*, although used in ordinary speech, do not express the temperature of a substance, and this fact has led to the adoption of certain thermometric scales.

53. Measurement of temperature.—*a.* A thermometer is any type of instrument made for the measurement of temperature. Precisely, it measures its own temperature, which is made to agree with what it is desired to measure. All sorts of thermometers depend upon heat effects (changes in dimensions, pressure, electrical resistance, heat radiation, etc.), but these are so numerous that only a few types of thermometers will be discussed in this study.

b. The action of the liquid, solid, and gas thermometer depends upon expansion by heat; for a liquid thermometer it would be the difference of expansion of the liquid and the glass. When a substance is being heated, the agitation of its particles pushes them a little farther apart on account of the increased vigor of their impacts. Solids show but a small change. A few alloys shrink with increase of temperature, but this is unusual. Evidently no single explanation of thermal expansion is adequate for all cases.

54. Thermal expansion of solids.—A common method of measuring the expansion of solids is to heat a metal rod and observe the change

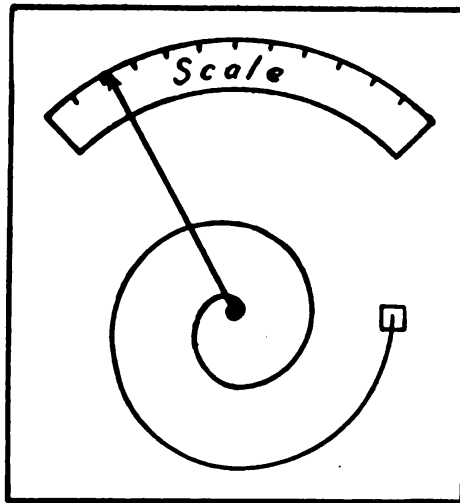


FIGURE 38.—Expansion type metal thermometer.

in length by means of a micrometer. This change depends upon the kind of material, the change in temperature, and the length of the rod. The expression in centimeters per degree centigrade in temperature is known as the linear coefficient of expansion. If K is this coefficient, L the length of the rod, T the change of temperature, and e the change of length, then:

$$e = LKT \text{ or } L = L_0 (1 - KT) \text{ (when } L_0 \text{ equals the original length).}$$

TABLE IV.—*Linear coefficient of solids*

[Expansion of 1 cm for 1° C. change]	
Iron.....	0.000011
Aluminum.....	.000025
Platinum.....	.000009
Brass.....	.000018
Glass (sodium).....	.0000085
Glass (lead).....	.000003

55. Bimetallic thermometer.—If two thin strips of different materials are fastened together and one end is held fixed, the free end will move with small changes in temperature. Such devices are used as metallic thermometers; or their motions may be made to close circuits automatically, as in the thermostat.

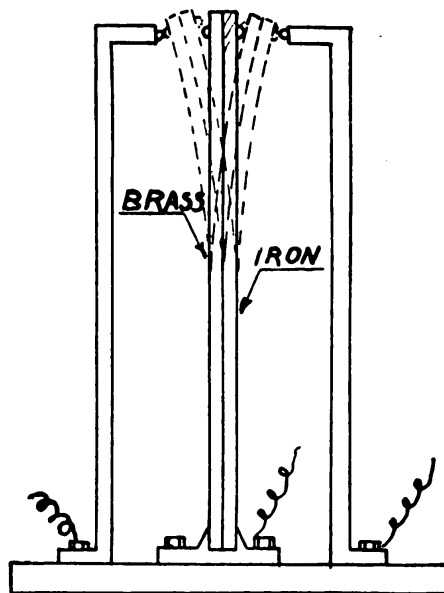


FIGURE 39.—Schematic principle of bimetallic thermostat

56. The resistance thermometer.—In measuring temperatures above 100°C. , scientists frequently employ electrical methods. Since the resistance of a metallic conductor usually increases with increase in temperature, a device for measuring electrical resistance can be made to act as a thermometer.

57. Thermometer scales.—Galileo is credited with the invention of the first thermometer. His instrument, however, measured only temperature differences. Later, Hooke proposed that the melting point of ice should be taken as a standard on which to found a scale of temperature. Still later it was discovered that two fixed points were necessary for a successful scale. Consequently the boiling point of water was taken for the other fixed point. Various fixed points were tried, but the boiling and freezing points of water were established as a standard.

a. Fixed points.—(1) The lower fixed point on the thermometric scale, called 0°C. or 32°F. , is the temperature at which pure ice and water can remain in equilibrium without any change in their relative amounts.

(2) The upper fixed point on the thermometric scale, called 100°C.

or 212° F., is the temperature existing in the steam above boiling water and under standard atmospheric pressure (1.013 millibars).

b. Centigrade and Fahrenheit.—(1) The centigrade scale, devised by Anders Celcius, Swedish astronomer, is universally used for scientific measurements. The Fahrenheit scale, named after the German physicist Gabriel Fahrenheit, is used largely for engineering and household purposes in England and the United States.

TEMPERATURE SCALES

Boiling point of water.....	F. 212°	C. 100°
Melting point of ice.....	32°	0°
Division between fixed points.....	180	100

(2) It is frequently necessary to convert temperatures from one scale to the other. In this process it must be observed that on the Fahrenheit scale there are 180 divisions, while the centigrade scale has only 100 divisions for the same temperature range.

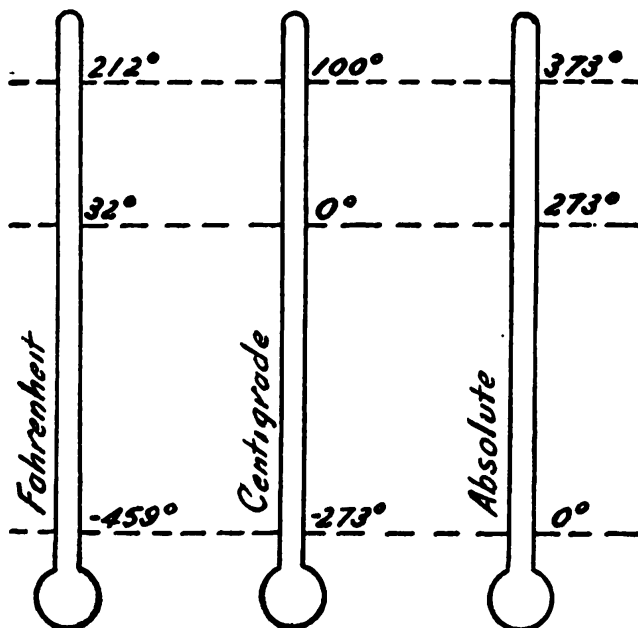


FIGURE 40.—Comparison of temperature scales: Fahrenheit, Centigrade, and Absolute.

For conversion from centigrade to Fahrenheit temperatures the following formulas will be useful:

$$T_f = \frac{9T_c}{5} + 32 \text{ and}$$

$$T_c = \frac{5}{9}(T_f - 32).$$

(3) On the Absolute or Kelvin scale, zero degrees is the lowest temperature theoretically obtainable. That is, if all the heat energy

were taken from a body, the temperature of that body would be absolute zero. This value would correspond to -273°C. or -459°F. Absolute zero may also be described as that point where both the temperature of a body and the quantity of heat which it possesses will be zero, or that point where molecular motion ceases.

58. The mercury thermometer.—This thermometer consists of a thick-walled glass tube with a very fine central hole down its axis drawn as uniformly as possible and sealed to a thin-walled bulb, usually cylindrical. The top of the tube is sealed off when the tube contains nothing but mercury. The positions of the mercury at 0°C. and 100°C. are marked off, and then the space between is graduated. The scale may be extended beyond the fixed points if necessary. Other liquids may also be used in thermometers; but as mercury possesses many favorable properties, it is used extensively. Some of these properties are the following: Freezing point -38.7°C. , boiling point $+357^{\circ}\text{C.}$, high specific gravity, low vapor tension, and a uniform rate of expansion.

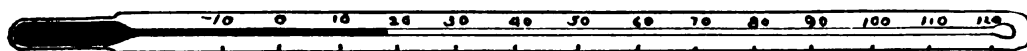


FIGURE 41.—Mercury thermometer.

59. Alcohol thermometers.—Alcohol and some other liquids have an advantage over mercury in their greater coefficient of expansion and smaller surface tension, but they are seldom used for accurate thermometers. Since the freezing point of alcohol is -78°C. , which is lower than that of mercury, it is used frequently in thermometers for measuring low temperatures.

60. Maximum thermometers.—A maximum thermometer is a device used for recording the maximum point reached by the end of the mercury column. There are two types of maximum thermometers. In the first, a small metal index (usually iron) is pushed ahead of the expanding mercury column. When the mercury column contracts, the highest temperature is indicated by the position of the lower end of the iron index. In the second type a constriction is made in the bore of the tube near the bulb, and at this point the mercury breaks. When contraction occurs after the maximum temperature has been reached, the mercury in the tube will not return through the constriction. Thus, the highest temperature for any period of time is indicated by the top of the mercury column. In either type the thermometer must be set before a maximum reading for a given period of time may be obtained.

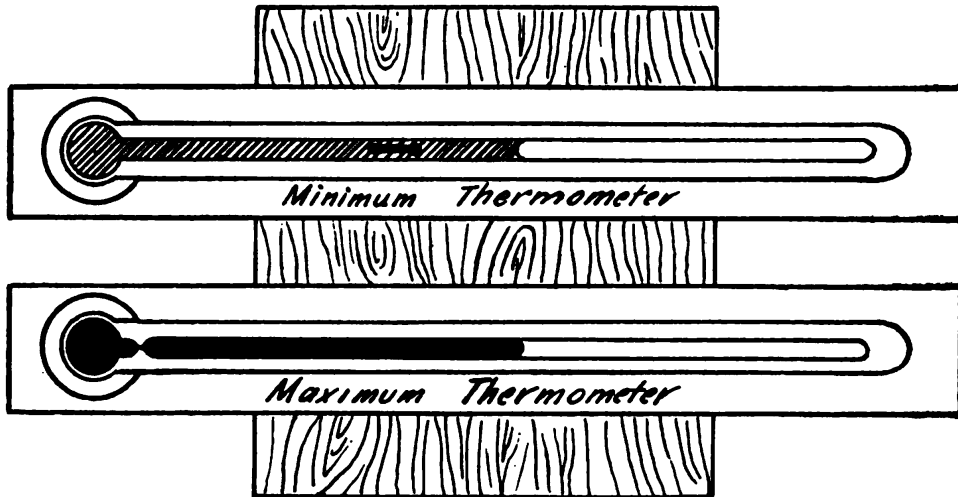


FIGURE 42.—Maximum and minimum thermometers.

61. Minimum thermometers.—A minimum thermometer is an instrument that records the lowest temperature in a given period of time. It is made of glass and alcohol. Within the alcohol in the tube is a small slider. When the temperature drops, this slider is carried down with the top of the alcohol. If the temperature rises, the slider will remain at the lowest position to which the alcohol surface dropped, the alcohol flowing past the slider as the temperature rises.

62. The gas thermometer.—*a.* Galileo discovered that gases expanded with increased temperature, and one of the first thermometers based on this principle was invented by him. There are two types of gas thermometers. In one, the gas is allowed to expand under constant pressure and the volume is measured. In the other, the volume is kept constant and the changes in pressure are noted. Here the latter will be discussed.

b. In figure 43 the bulb *A* containing the gas is connected to *C* by a small glass tube *B*. The flexible tube *CDE* is attached to an open glass tube *F*. The tube *DEF* is then filled with mercury. The volume of the gas in the bulb is held constant by adjustment of the height of the tube *F* so that the mercury surface at *C* is always at the same position. The height of the mercury surface in the tube *F* is a measure of the pressure of the gas in the bulb and therefore also a measure of the temperature of the bulb, pressure being proportional to absolute temperature at constant volume. When properly calibrated, this device operates as an accurate and reliable thermometer.

c. There is a similar instrument in which the pressure is kept constant so that the volume which the gas assumes may be measured.

As the volume of a sample of gas is proportional to the absolute temperature at constant pressure, the volume of the gas may be used as a direct measure of temperature.

63. Metal thermometers.—*a.* Metal thermometers are coming into use more and more. In fact, for the measurement of high temperatures they are the most accurate of all types. It has been stated before that the resistance of a coil of wire to the passage of an electric current changes with temperature, and from these changes an instrument can be calibrated for measuring temperature.

b. The instrument consists primarily of a coil of wire (usually platinum) mounted in a protecting tube of glass, metal, or porcelain.

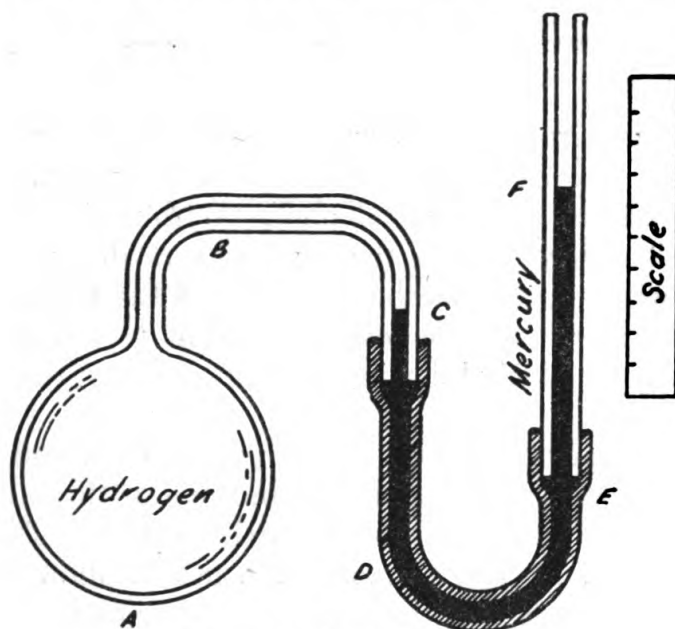


FIGURE 43.—Gas thermometer.

A Wheatstone Bridge is connected in the circuit, and from the resistance reading, the temperature may be calculated.

c. Metal thermometers offer several distinct advantages over other types. They are very durable and reliable. They give reliably accurate readings over a great range of temperature. They may be used either for indicating or for recording at a distance from the actual thermometer. Because of these advantages the metal resistance thermometer is being used more and more in industrial and scientific applications.

64. Calorimetry.—The process of measuring heat quantities is called calorimetry. When two bodies of different temperatures are

placed in good contact with each other, the hot body gives up heat and the cold body takes on heat until both reach the same temperature. This reaction may be stated thus: "Heat lost by one body equals heat gained by the other body, provided no heat is gained from, or given to, the surroundings."

65. Unit of heat.—The unit for measuring heat is the calorie. It may be defined as that quantity of heat required to raise the temperature of 1 gr of water 1° C.

66. Specific heat.—*a.* Specific heat (*s*) is defined as the number of calories required to raise the temperature of 1 gr of a substance 1° C. The specific heat of water is 1, since 1 calorie is required to raise the temperature of 1 gr of water 1° C.

b. We know that certain bodies are more difficult to heat than others and that these same bodies also retain heat longer. For instance, if the same source of heat is applied to equal weights of water and iron, a longer period of time is required to increase the temperature of the water 10° than is required for the iron. Also it is true that to increase by 50° the temperature of 10 pounds of water requires a longer time than to increase by the same amount the temperature of one pound of water. The specific heat of different substances varies, as may be seen in the following table:

TABLE V.—*Specific heats*

	Cal./gr/degree
Aluminum.....	0.21
Brass.....	.088
Copper.....	.093
Glass.....	.200
Ice.....	.500
Iron.....	.113
Lead.....	.031

c. It is also true that the specific heat of a substance changes with its existing state. For example, ice has a lower specific heat than water; that is, it takes only approximately half as many calories to change the temperature of a given amount of ice as it takes for the same amount of water.

67. Heat capacity.—The ratio of the heat capacity of a substance to the heat capacity of an equal quantity of water is called the specific heat of the substance. It follows, then, that heat capacity is the quantity of heat necessary to raise the temperature of a given body 1° C. or the quantity of heat released by a body when its temperature is lowered 1 degree. If we let *Q* represent the heat capacity,

M the mass, S the specific heat, and T the temperature of the body, then:

$$Q = MST$$

(1) *Example:* 50 gr of lead in being raised from 20° C. to 100° C. will absorb $50 \times 0.031 \times 80 = 124$ calories.

(2) *Example:* 50 gr of lead are cooled from 200° C. to 50° C.; the heat lost will be $50 \times 0.031 \times 150 = 232.5$ calories.

68. Method of mixtures.—*a.* If two bodies of different temperatures are mixed, an equilibrium temperature will be reached by the mixture. For instance, if a ball of hot iron is placed in a container of cold water, the water plus the container will gain heat, and finally the mixture will have the same temperature.

b. If M_1 represents the mass, S_1 the specific heat, T_1 the temperature of one body; M_2 the mass, T_2 the temperature, S_2 the specific heat of the liquid; and T_m the temperature of the mixture, the following expression is true:

$$\begin{aligned} \text{Heat lost} &= \text{Heat gained} \\ (M_1) (S_1) (T_1 - T_m) &= (M_2) (S_2) (T_m - T_2) \end{aligned}$$

Problem: How much heat is required to raise the temperature of 100 gr of tin from 20° C. to 200° C.?

$$\begin{aligned} Q &= Ms(T_1 - T_2) \\ &= 100 \times 0.060 \times 180 \\ &= 108 \text{ calories} \end{aligned}$$

Problem: 100 gr of iron at 200° C. are placed in a copper calorimeter containing 200 gr. of water at 20° C. (The calorimeter weighs 130 gr. and is at the temperature of the water.) Find the temperature of the mixture.

$$\begin{aligned} \text{Heat lost} &= \text{Heat gained} \\ 100 \times 0.11 (200 - T_m) &= 200 \times 1 (T_m - 20) + 130 \times .093 (T_m - 20) \\ 100 \times (22 - .11 T_m) &= 200 \times (T_m - 20) + 130 \times (.093 T_m - 1.86) \\ 2200 - 11 T_m &= 200 T_m - 4000 + 12.09 T_m - 241.8 \\ 223.09 T_m &= 8618.6841.8 \\ 36.7 \\ T_m &= 38.6^\circ \text{ C.} \end{aligned}$$

QUESTIONS

1. What is the nature of temperature?
2. Define heat; temperature.
3. How is heat measured?

4. Explain the principle of a thermostat.
5. What are the "fixed points" of a thermometer and how are they determined?
6. Define and explain Absolute zero.
7. Give the advantages of a mercurial thermometer.
8. When is alcohol used in thermometers?
9. Explain the maximum and minimum thermometer.
10. What type of thermometer is used in measuring very high temperature? Why?

PROBLEMS

1. Mercury solidifies at -38.8°C . and vaporizes at 356.7°C . Express these temperatures on the Fahrenheit scale.
2. At what temperature are the readings of a Fahrenheit and a centigrade thermometer the same numerically?
3. Find the centigrade temperatures corresponding to 10°F . and 60°F .
4. A brass meter bar is found to be longer by 0.007 cm than an iron one at 25°C . At what temperature do they agree?
5. A brass tape correct at 0°C . is used to measure a section of a bridge when the temperature is 25°C . What is the percentage of error in the measurement due to the expansion of the tape?
6. The cables which support a bridge are 1,000 m long. What is the total change in length which occurs between a temperature of -20°C . in the winter and a temperature of 30°C . in the summer? (Coefficient of expansion = 0.000012.)
7. What is the temperature of 1 liter of water at 30°C . after 500 calories have been added to it?
8. A liter of water is cooled from 30°C . to 5°C . How much heat is given off in the process?
9. How much heat is necessary to raise the temperature of a block of iron weighing 2.2 kg from 10° to 130°C .?
10. A bath tub (mass 40 kg, specific heat 0.1) contains 150 liters of water at 15°C . It is desired to warm it up to 35°C . How many liters of boiling water must be added, assuming that no heat is lost by conduction or otherwise?
11. 200 gr of lead at 110°C . are mixed with 300 gr of water at 20°C . What is the final temperature of the mixture?

SECTION X

HEATING OF THE ATMOSPHERE

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Source of the earth's heat.....	69
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69. Source of the earth's heat.—*a.* The sun is the source of all terrestrial energy that has any practical significance for man. It is a body 800,000 miles in diameter and has a temperature of about 6,000° A. It radiates energy at the tremendous rate of 60,000 hp from every square yard of its surface. The earth, 93,000,000 miles away, receives this energy at the rate of about 1 hp per square yard.

b. The energy which comes to the surface of the earth by conduction from the earth's interior and that which comes from the planets and stars of outer space is small in comparison. The unequal amounts of solar energy absorbed by unit areas over the earth, from the equator to the poles, and Nature's method of equalizing this energy give rise to all our wind movements, cyclonic systems, thunderstorms, precipitation, etc. In this chapter we shall discuss how the sun's energy is received and distributed by the atmosphere.

70. Transmission of heat.—There are three ways by which heat energy may be transferred from one place to another: radiation, convection, and conduction. Each performs a significant role in the heating of the atmosphere.

71. Radiation.—*a.* Radiation is the process by which energy is transmitted through space without the presence of matter. Heat and light are transmitted from the sun in this manner at the velocity of light, which is 186,000 miles per second. It is unchanged in quantity and quality until it is intercepted by matter. The solar radiation which comes to the earth and which plays such an important part in our weather is given the special name of insolation.

b. Radiation is thought to be a wave disturbance analogous to the waves which travel over a water surface. The characteristics of a radiation wave are the period and the wavelength. Radiant heat and

light are alike, not only in that they travel at the same speed but also in that they can both be refracted by lenses and prisms. These and other facts prove that radiation waves are of exactly the same nature as light waves. Light consists simply of radiation waves, which affect the eye, and are between 0.0004 and 0.00076 mm in length.

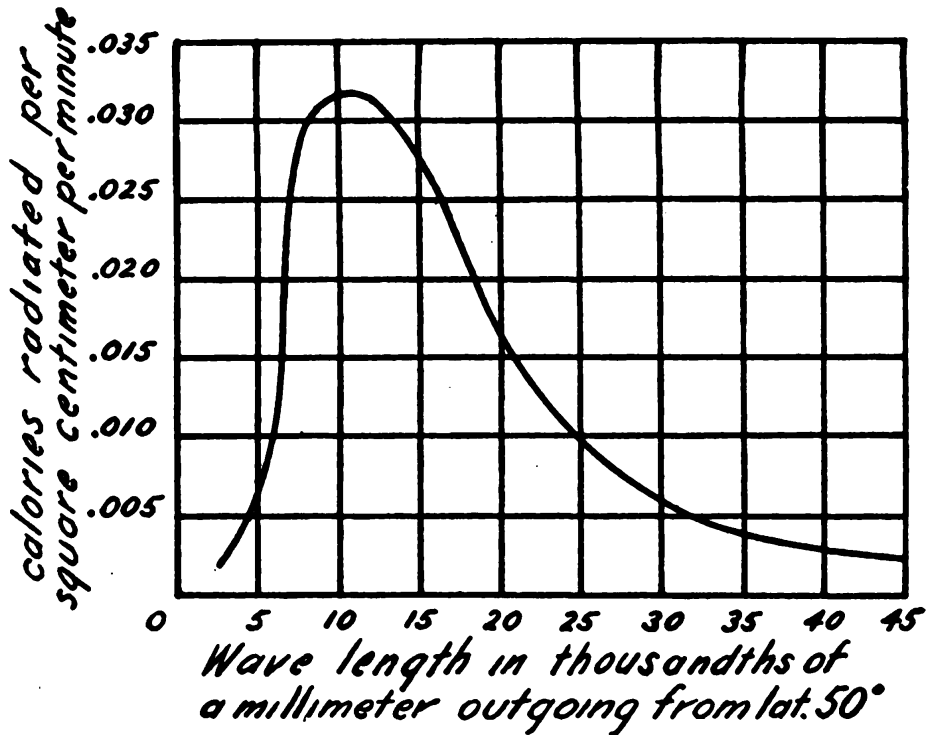


FIGURE 44.—Radiation from the earth, showing intensity as a function of wave length.

72. Radiation, absorption, and reflection.—There is a direct relationship between radiation, absorption, and reflection. It has been found that a body which is a good radiator is also a good absorber. The hotter the body, the more rapidly radiant energy is sent out. Since every body is radiating (unless it is at absolute zero), every body must also be absorbing. An easy way to prove that there is a close connection between the absorbing power and the radiating power of an object is to heat a piece of white china with dark markings in an oven. At ordinary temperatures the markings look dark because they absorb more light, but at high temperatures they look bright against the china because they radiate more. The reflecting power of a surface is the ratio of the radiant energy reflected from the surface to the energy incident upon it. The reflecting power of a surface is also different for different substances; i. e., a polished silver surface will reflect more than a polished iron surface.

73. Factors governing insolation received.—*a.* The amount of insolation that any particular area of the earth receives is dependent on several different conditions. One of the most important of these conditions is the angle of inclination. The more nearly overhead the sun is, the greater will be the insolation.

b. The distance from the earth to the sun varies from 91,500,000 miles in January to 94,500,000 miles in July. This periodic variation causes 7 percent more energy to arrive at the earth in January than in July, and will have a tendency to make the winter temperature

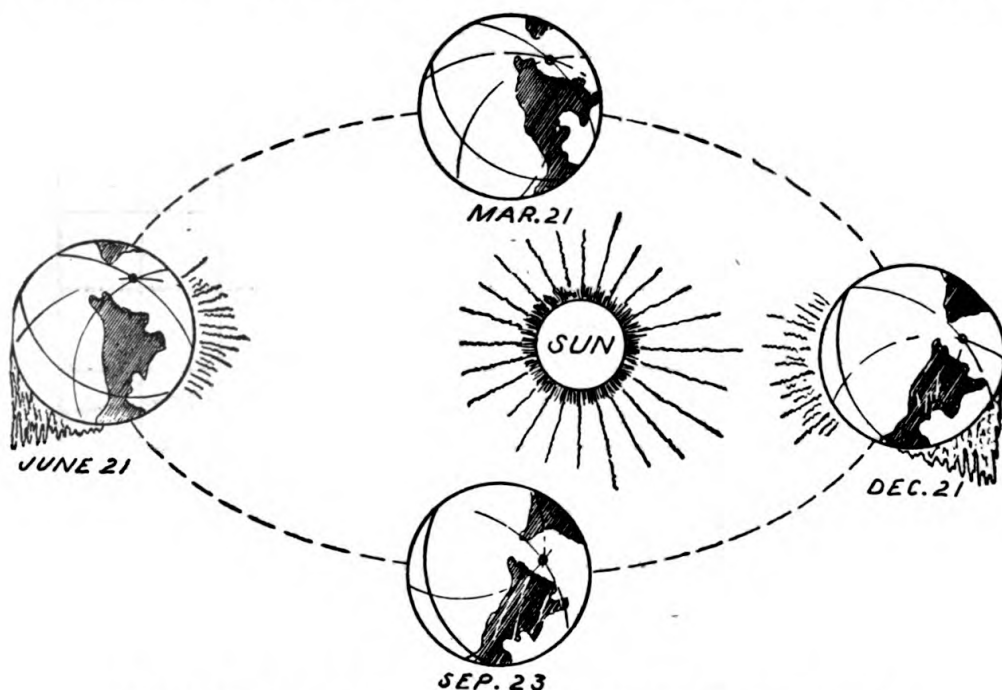


FIGURE 45.—Position of the earth with relation to the sun at different seasons.

higher and the summer temperature lower in the Northern Hemisphere. The reverse effect would be observed in the Southern Hemisphere. The moderating effect of the large water bodies of the Southern Hemisphere, however, make it difficult to observe any particular difference in the annual range of temperatures of the two hemispheres.

c. At the outer reaches of our atmosphere, insolation is coming in at the rate of 1.94 calories (approximately 2.0) per square centimeter per minute, and this value is known as the solar constant. It is equivalent to 1.5 hp. per square yard. It has been observed that the solar constant varies over a period of years by as much as 2 percent and that the period of its variation agrees somewhat with the sun spot cycle. The direct effect upon the world weather of this change is not known, but certainly some effects exist and in time will be

known and used in long range forecasting and in the study of world weather trends.

d. Not all of the sun's energy that is directed toward the earth reaches it. A great amount is reflected back by clouds. The amounts of cloudiness, averaged for the entire earth for the whole year, has been found to be 42 percent. This figure will be used to show the transmission and absorption of the earth's atmosphere in figure 46.

74. Terrestrial and solar radiation.—*a.* Let us consider the difference in wavelengths of the energy coming from sources of different temperatures. Because of the high temperature of the sun, the bulk of the incoming solar radiation is of short wavelength, which is in the visible range of the spectrum. This short wave energy penetrates the atmosphere more readily and is absorbed in less quantity than the long wave energy. Also, it is scattered more than the long infrared waves. Most of the energy which reaches the earth is absorbed. It warms the material upon which it falls, and is in turn radiated out into the atmosphere and into space. However, this radiation is in the form of long waves, characteristic of a body of the earth's radiating temperature, which is about 280° A. There must be a balance of the incoming short wave solar radiation and the outgoing long wave earth radiation, because the temperature of the atmosphere and earth remains approximately constant over a long period of time.

b. This balance of energy is shown in figure 46. Of the total energy radiated to the earth from the sun, 33 percent is reflected at once into space by clouds, water vapor, and dust. Twenty-five percent is scattered radiation through the atmosphere; of this amount 9 percent is returned to outer space and 16 percent is reradiated to the earth. It will be noted that the 33 percent reflected by the clouds and the 25 percent scattered in radiation through the atmosphere will leave 42 percent of the sun's energy bound directly for the earth's surface. Of this 42 percent the atmosphere will absorb 15 percent before the energy reaches the earth. Thus only 27 percent of the sun's total energy strikes the earth directly. But it will be recalled that of the scattered radiation in the atmosphere 16 percent is reradiated to the earth. The final total received and absorbed by the earth is, then, 43 percent, or the sum of the direct radiation from the sun and the reradiation from the atmosphere. The 15 percent absorbed by the atmosphere and the 43 percent absorbed by the earth are used to (1) warm the lands and water; (2) produce evaporation from soil, ocean, and clouds; (3) melt snow; and (4) produce the photosynthesis in plant life. Of the 43 percent absorbed by the earth, 8 percent is radiated directly into space, 16 percent is radiated to the atmosphere

and is absorbed, and 23 percent is transmitted to the atmosphere by water vapor and convection. Of this 23 percent transmitted to the atmosphere, 4 percent is again returned to the earth by downward convection currents. The atmosphere radiates the same amount of energy which it receives. If this were not the case, there would be a building up or a lowering of the temperature of the atmosphere, a phenomenon which is known not to be true.

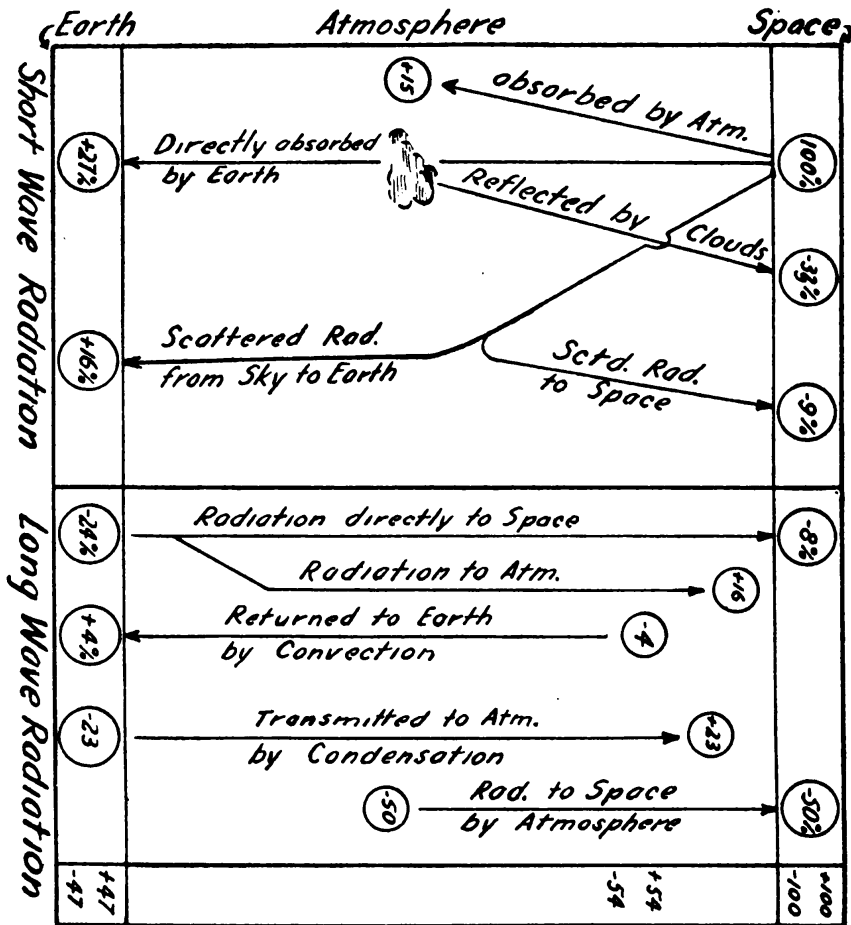


FIGURE 46.—Balance of heat gained and lost by the earth and its atmosphere.

c. *Greenhouse effect.*—This whole process is well illustrated in the principle operative in a greenhouse, where short waves penetrate the glass roof and warm the soil and vegetables. The warmed interior radiates long heat waves to which the glass roof is opaque. The greenhouse is, therefore, warmed to a much higher temperature until by conduction and radiation a heat balance is established with its surroundings.

75. Conduction.—a. Conduction is the flow of heat through matter unaccompanied by any motion of the matter; in other words, the transfer of heat from molecule to molecule. The rate of flow

from the body of higher temperature to the body of lower temperature is dependent upon the temperature difference. Heat will be conducted faster if the temperature difference is greater. The rate of flow of heat, other conditions being equal, also depends upon the material through which it must flow; substances are roughly divisible into "good conductors" which permit, under given conditions, a large flow of heat and which in general are metallic, and "poor conductors" which permit a small flow of heat and are in general nonmetallic, such as wood, glass, asbestos, leather, and linen.

b. The conductivity of liquids is, in general, about equal to that of solids of low conductivity except that mercury, which is metallic, is a good conductor. Water and some aqueous salt solutions have conductivity coefficients between the metallic and the nonmetallic solid conductors.

c. The conductivity of gases is comparatively low. For this reason, air layers enclosed in or between solids, such as air spaces in house walls, in walls of refrigerators, in pores in cloth, and in fur or feathers, are chiefly responsible for the low conductivity found in these cases.

d. Conduction is a major heat transfer process in the atmosphere. The earth and its vegetation are very good absorbers of solar energy and are readily warmed when exposed to it. They are likewise efficient radiators of the earth's energy and rapidly cool off after sunset. The atmosphere in contact with these areas is warmed or cooled by conduction. This heating and cooling would extend a distance of only a few feet above the surface were it not for convection and surface turbulence, which continually bring fresh air into contact with the surfaces. Thermometers placed in the surface of the soil and a few feet above the surface show a large difference in temperature, the air temperature lagging behind that of the soil. This poor conducting property of the air is the reason for temperature inversion near the ground and often causes the ground fogs observed early in the morning. Temperature inversion is explained in paragraph 82. Fogs and their causes will be fully explained later in the weather course.

76. Convection.—Convection is the transport of heat by moving matter, for example, by the hot air which can be felt rising from a hot stove. In connection with weather, convection refers to the upward or downward movement of a limited portion of the atmosphere, the movement having been induced by some mechanical or thermal action. Gases upon being heated expand and become less dense. When the atmosphere is heated at the equator or any localized area, it is pushed aloft by the colder, heavier air in its neighborhood, thus carrying this surface heat to higher elevations. Cumuliform clouds and dust whirls

are visible evidence of these vertical convections. Horizontal convection also occurs in the local and general wind systems of the earth as a result of unequal surface heating and cooling.

77. Heat balance in the atmosphere.—*a.* The curve in figure 47 shows the relationship of the incoming solar radiation (curve I) and the outgoing terrestrial radiation (curve II) as a function of latitude. Note that at latitudes less than 37 degrees the solar radiation exceeds

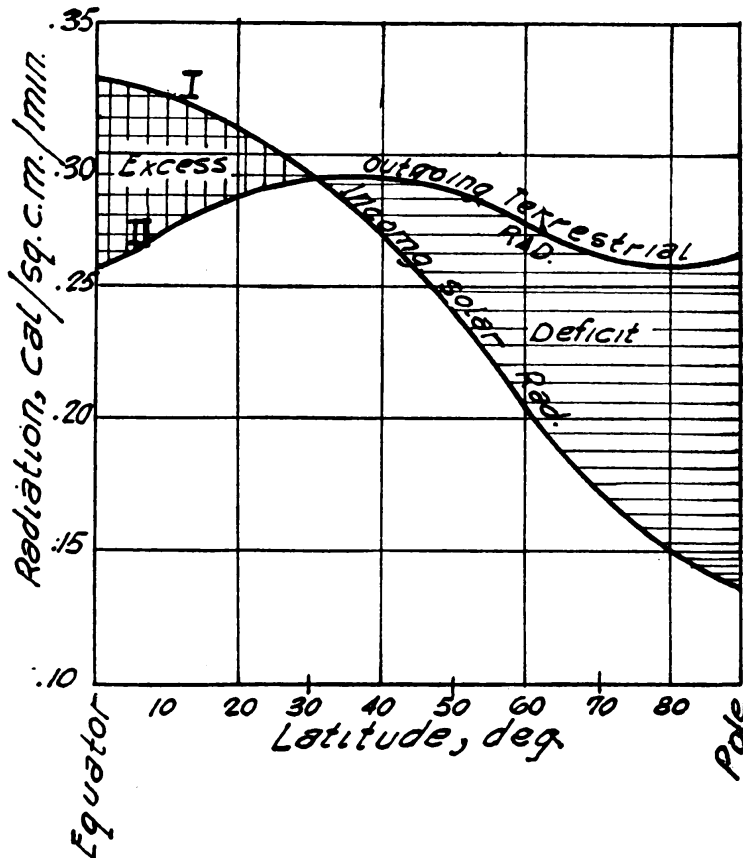


FIGURE 47.—Relation of incoming and outgoing radiation at each latitude.

the outgoing radiations, thereby causing a continual increase of temperature. Above 37 degrees latitude outgoing earth radiation is greater than that coming in, causing a continual decrease in temperature. There is, however, a convectional current to balance this great difference. In this unequal distribution of solar and terrestrial radiation lies the ultimate cause of all atmospheric motion, for it is only through these motions that the heat differences can be equalized. Convectional currents are the main cause of the bumpiness that is experienced when flying. In extreme instances, for example, thunderstorms, these upcurrents can cause serious accidents to aircraft.

b. Advection, which is a form of convection, is the process of transfer by horizontal air movements. This, then, is the method of transfer when one air mass replaces another air mass.

c. Two objects in contact with each other and having different temperatures will tend toward an average temperature. The object having the higher temperature will give up some of its heat, lowering its own temperature, while the object having the lower temperature will take up this heat and raise its own temperature. Eventually the two objects will have the same temperature. This equalization process also applies to an air mass over a land surface. Air near the surface of the earth tends to acquire the same temperature as the surface. Over a cold surface may be found cold air; over a warm surface, warm air. Cold air moving over a warm surface will become warmer; warm air moving over a cold surface will become colder. If the air mass remains over the surface for a considerable length of time, the entire air mass will tend to assume the characteristics of the underlying surface.

78. Normal lapse rate.—*a.* All pilots have probably at one time or another noticed that as they rise in altitude the temperature of the air decreases. If the amount of temperature decrease with increase in altitude were averaged for a great many cases, it would be found that the air temperature usually falls off $2^{\circ}\text{C.}/1,000$ feet increase in elevation (equal to $6^{\circ}\text{C.}/\text{km}$). This is called the *normal lapse rate*. As an example consider air over the North Pacific Ocean. If the surface air temperature is 20°C. , the air temperature at 10,000 feet will be 0°C. ($2^{\circ}/1,000 \times 10 = 20^{\circ}$, the temperature drop at 10,000 feet). Similar computation is useful in determining the elevation at which a pilot may encounter icing. This decrease of temperature with altitude continues up to the tropopause, which is a surface separating the troposphere from the stratosphere above. In the stratosphere there is no longer a lowering of temperature as the elevation increases. Figure 48, a free air sounding, shows how the temperature drops off with increase in altitude up to the tropopause; then the temperature no longer decreases with increase in altitude.

b. As has already been pointed out, different parts of the earth, such as the equatorial regions, are heated more than other parts, such as the polar regions. Since the atmosphere tends to get the same temperature as the surface, we find cold air masses over the poles and warm air masses over the equator. The cold air is more dense and hence will form a high pressure area; whereas the warm air, being less dense, will form a low pressure area. It is these differences in pressure that cause the movement of air masses with their resultant winds.

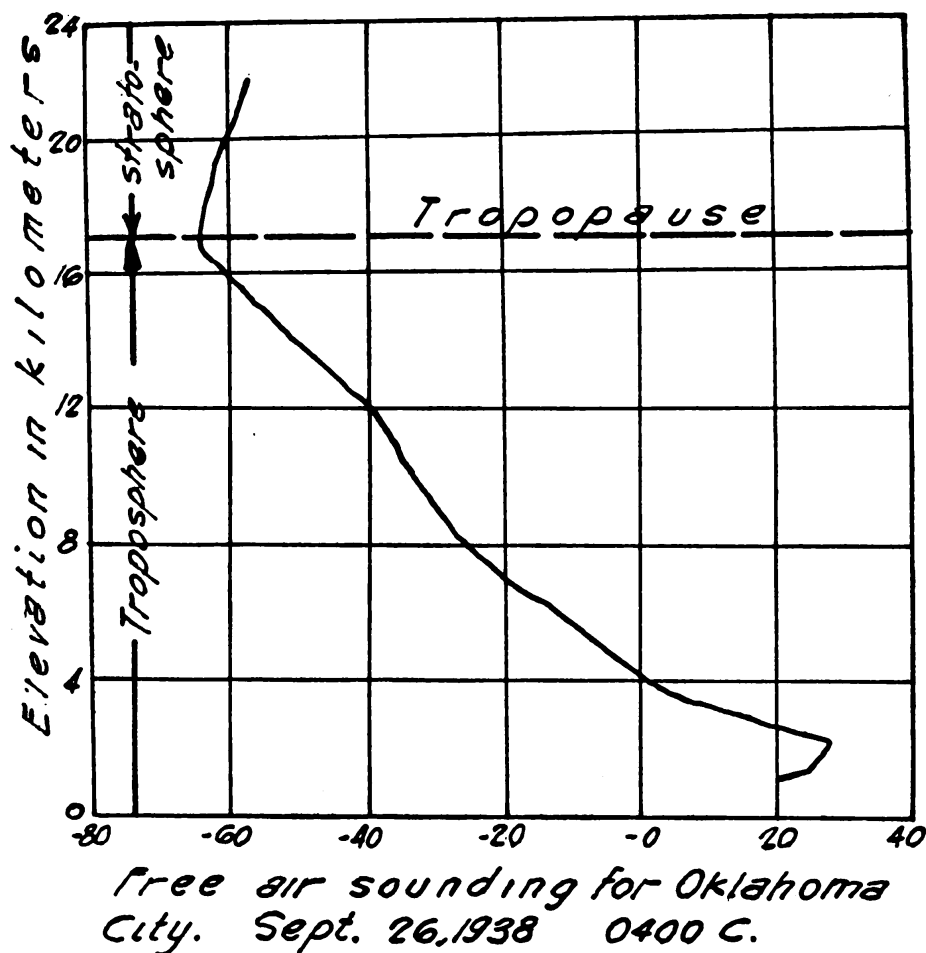


FIGURE 48.—Temperature of the upper atmosphere at night.

The high pressure will tend to push down to neutralize the low pressure areas.

79. Daily variation in temperature.—*a. Over land.*—Figure 49 shows the changes in temperature in the atmosphere from night to day. During the day the temperature near the ground increases, and as warm air is light it tends to rise in convective currents. At night the condition is reversed. The ground loses heat by radiation, cooling off the lower layers of the air. The cold air next to the ground is heavy and tends to remain at the ground. This condition is called an inversion because the temperature increases with height instead of decreasing, as is usually the case. An inversion is a stable condition, and convective currents do not occur in stable air.

b. Over ocean.—There is little change in water surface temperature from night to day. Hence the surface air temperature does not vary much, but the atmosphere at the higher elevations can still cool off at night by radiation. If the upper air cools while the lower air

remains at the same temperature, the effect is similar to heating from below, though no actual heating has taken place. Under such conditions the air becomes unstable and convective currents may arise in

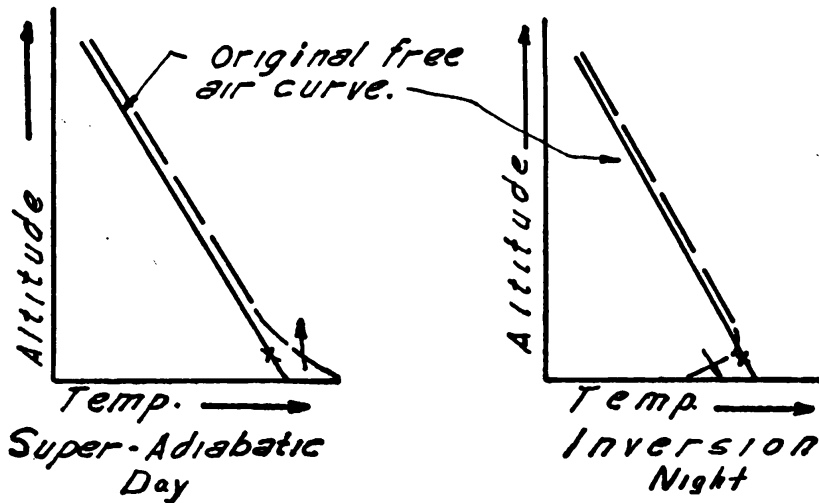


FIGURE 49.—Temperature of the lower atmosphere.

the same way as over the land, where actual heating occurs from below. Thunderstorms are a result of convective instability and consequently occur over the ocean chiefly at night.

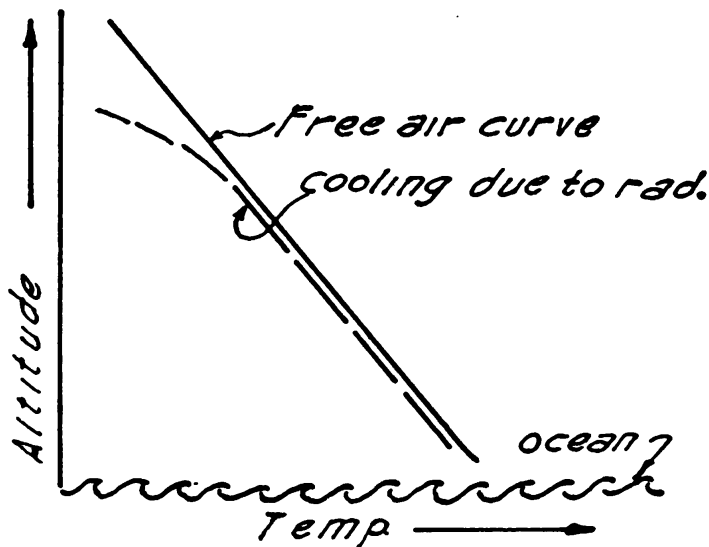


FIGURE 50.—Cooling of the air over the ocean.

QUESTIONS AND PROBLEMS

1. Name the three methods of heat transfer and give an example found in Nature of each method.
2. From the standpoint of heat radiation and absorption: (a) What color should winter clothes have? (b) What finish should the sides of a teakettle have?

3. Why should steam radiators be installed on the cold sides of a room?
4. Explain why the atmosphere receives more energy indirectly from the earth than it receives directly from the sun.
5. Would you expect bumpier flying conditions over land at night or in midafternoon? Over the ocean? Explain briefly.
6. If a door is opened between a warm and a cold room, in what direction will a candle flame placed at the top of the door be blown?
7. The earth's atmosphere has been likened to a greenhouse. Explain why you would expect to find higher temperatures inside the greenhouse than in the outside air.
8. Parts of the earth are heated more than others. Explain why this would cause a general circulation of air from the north in lower altitudes (in the Northern Hemisphere).
9. If the surface air temperature over the Atlantic Ocean is $24^{\circ}\text{C}.$, how high could one fly before getting into subfreezing air?
10. Why does the fleece lining of a winter flying suit keep one warm?

SECTION XI

PROPERTIES OF GASES

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80. Kinetic theory.—*a. Molecular structure of a gas.*—Present-day theories of the structure of gases are based on a great many different methods of investigation. The kinetic theory, described below, seems to explain best all the experimental evidence of the properties of gases. This theory presupposes that a gas is composed of a great many tiny molecules, each a unit in itself, separated by distances of free space relatively large compared with the size of the molecules. These molecules have almost no attraction for each other and move with high velocity in purely random motion. The only important interference with this motion is the frequent collision of the molecules with other molecules and with the sides of the container which holds the gas. These molecules are extremely small, and very large numbers of them are present in any normal quantity of gas. For example, 29 grams of air, 32 grams of oxygen, or 18 grams of water vapor each contain 6.06×10^{23} molecules (606 followed by 21 zeros).

b. Pressure in gases.—It is easy to see that a great number of collisions occur between these molecules and any solid wall. Each individual collision causes a small impulse against the wall, but the collisions occur with such great frequency that there is a continuous effect of force against the wall perpendicular to its surface. This force is called the pressure of the gas, and every gas exerts a pressure in some degree, even when highly rarefied. The pressure of the gas against any wall will depend upon the number of collisions per second, upon the mass of the molecules, and upon the velocity of their movement.

81. Boyle's law.—*a.* From experience it is known that any gas is compressible to some extent, and this compression is accomplished only by exerting some force on the gas (that is, increasing the pressure). Boyle's law mathematically expresses the relationship between pressure and volume: *In any sample of gas the volume is inversely proportional to the pressure if the temperature is held constant.* This may be expressed by the equation:

$$P_1V_1=P_2V_2$$

P_1 and V_1 are known pressures and volumes; P_2 and V_2 are some other pressure and volume at the same temperature.

b. This may be explained by the kinetic theory, as follows: A decrease in the volume of a given quantity of gas results in a higher concentration of molecules by causing a specified number to occupy a smaller space. This higher concentration of molecules must of necessity result in more collisions and therefore higher pressure.

82. Charles' law.—According to the kinetic theory of gases, the temperature of a gas is determined solely by the kinetic energy of its molecules. This means that the molecules are going faster at higher temperatures than at lower temperatures. An increase of velocity means that the molecules are going to strike the walls harder than before and, furthermore, that there are going to be more collisions. At a temperature of absolute zero the velocity of the molecules is zero. As the temperature increases, the motion of the molecules increases in such a way that the sum of the kinetic energies of all the molecules in a given mass of gas is directly proportional to the absolute temperature. This results in an increase in pressure exerted by the gas if the volume of the sample is held constant and the temperature is increased. The relationship between pressure and temperature is expressed mathematically by Charles' law: *In any sample of gas at constant volume, the pressure is directly proportional to the absolute temperature.* In equation form this would be:

$$P_1T_2=P_2T_1$$

P_1 and T_1 are some known pressure and absolute temperature; and P_2 and T_2 are some other temperature and pressure. These temperatures are based on the absolute scale where 0° Absolute corresponds to -273° centigrade and 300° Absolute would correspond to 27° centigrade.

Example: If air is admitted to a cylinder of a gasoline engine at atmospheric pressure 14 lb. per square inch), what will be the total pressure on the air when the piston has moved so that the volume of the air is reduced to one-fifth the initial volume and the temperature is not allowed to increase?

$$\begin{aligned} P_1 V_1 &= P_2 V_2 \\ \text{or } 14 V_1 &= P_2 \left(\frac{1}{5} V_1 \right) \\ P_2 &= 5 \times 14 = 70 \text{ lb per square inch.} \end{aligned}$$

A pressure gage reads only the difference between the internal and atmospheric pressure. What would such a gage read in the above example?

$$P = 70 - 14 = 56 \text{ lbs per square inch}$$

Example: Automobile tires often blow out because of the increased pressure, as the tires get hot in fast driving. If tires are filled to a gage reading of 30 pounds per square inch at night when the temperature is 0° C., what will be the gage pressure if the tires reach a temperature of 60° C. the next day?

Solution:

Initial pressure total is $14 + 30$ or 44 lbs per sq in

Initial absolute temperature is 273°

Final absolute temperature is 333°

$$P_1 T_2 = P_2 T_1$$

$$44(333) = P_2(273)$$

$$P_2 = \frac{44(333)}{273} = 53.7$$

$$\text{Gage pressure} = 53.7 - 14 = 39.7 \text{ lb per sq in}$$

83. General gas equation.—Boyle's and Charles' laws are the bases for a general equation of state for gases. This may be expressed as follows:

$$PV = MRT$$

As before, P , V , and T are the total pressure, the volume, and the absolute temperature, respectively. M is the mass of the gas, and R is a number whose value has been determined for every known gas. This number is always the same for any one type of gas, but each gas has its own R . If R is known for any gas, it is possible to

determine the pressure, the volume, or the temperature if all the other elements of the equation are known. In any given sample of gas, M and R are constant, and the equation may be set up as follows:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

P_1 , V_1 , and T_1 are the pressure, volume, and temperature of a sample of gas. P_2 , V_2 , and T_2 are any other conditions in the same gas sample.

Example: In the above example of the gasoline engine, assume that the gas explodes at the compressed position and the temperature rises from 20° C. to 1,000° C. What will be the pressure?

Solution:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{(14)(V_1)}{293} = \frac{P_2(5V_1)}{1273}$$

Cancel out V_1 and solve for P_2

$$P_2 = \frac{(5)(14)(1273)}{293} = 304 \text{ lbs per sq in total pressure.}$$

$$\text{Gage pressure} = 304 - 14 = 290 \text{ lbs per sq in.}$$

84. Adiabatic and isothermal processes.—*a.* According to Boyle's law, the pressure of a gas is inversely proportional to its volume if the temperature is held constant. Figure 51 is a chart showing how the pressure of a gas will increase with a decrease in volume if the temperature is held constant. On the curve for the temperature of 0° C., it may be seen that when the volume is reduced to one-tenth of that at the far right-hand side, the pressure has increased 10 times. The same relation will hold at any other temperature, provided that this temperature is held constant during the volume change. It should be noted also that at the higher temperature the pressure is higher for the same volume. Such a change in volume and pressure at a constant temperature is called an *isothermal* process.

b. Ordinarily, when a gas is compressed the temperature does not remain constant, but increases. If a compression or expansion is carried out in such a way that there is no heat added to or taken away from the gas, the process is called *adiabatic*. This is different from the isothermal process in that heat must be added or subtracted during the isothermal process to keep the temperature constant. Almost any rapid expansion or compression is approximately adiabatic. Adiabatic compression of a gas is always accompanied by an increase in temperature, and adiabatic expansion causes a cooling effect. In

Diesel engines air is rapidly compressed to a small fraction of its original volume, and the temperature is increased thereby so greatly that fuel sprayed into the gas will spontaneously ignite. The student has probably noticed that air which is allowed to escape from an automobile tire is very cold on the fingers because of a rapid adiabatic expansion upon release from the tire.

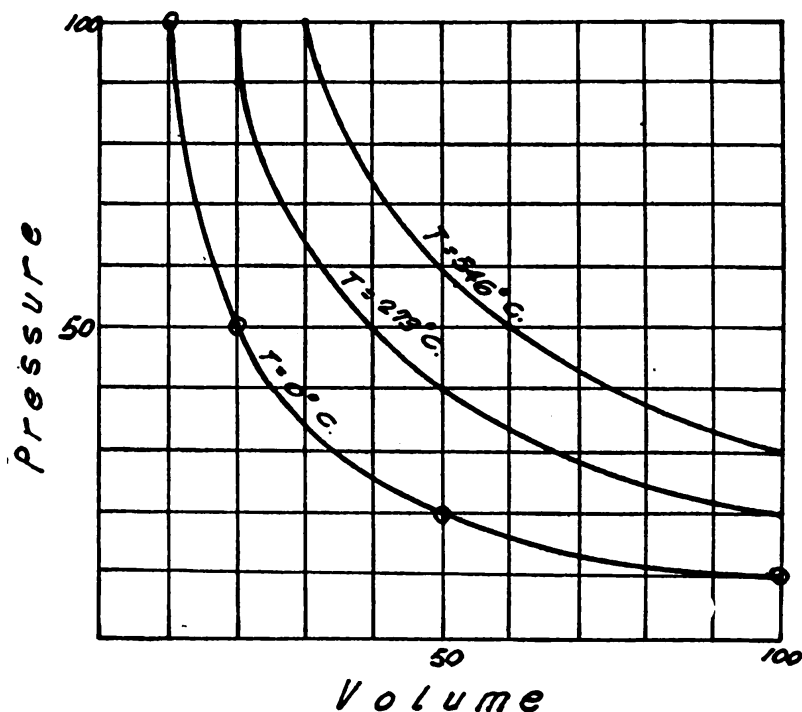


FIGURE 51.—Variation of pressure with volume of a gas at temperature of 0° C., 273° C., and 546° C.

c. The increase in temperature with adiabatic compression is caused by the simple fact that work is being done on the gas to compress it and thereby there has been an addition of energy to the gas which can only result in an increase in its temperature. Figure 52 shows the relationship between adiabatic and isothermal compression of a gas. On the right-hand side of the diagram we have the same sample of gas as in figure 51. As the volume is reduced by compression (moving left on the curve) it is found that the pressure increases to 10 times its former value when the volume has been reduced to only one-fifth its initial value. This is due to the fact that the temperature has reached twice its former value at this point. Mathematically the relationship between pressure and volume may be expressed as follows:

$$P_1 (V_1)^\gamma = P_2 (V_2)^\gamma$$

P_1 and V_1 are the pressure and volume before the change and P_2 and

V_2 are their values after the change. γ^1 is an exponent which depends upon the type of gas. Its value for air is about 1.4.

85. Adiabatic processes in the atmosphere.—Very often air in the atmosphere undergoes a great deal of lifting. At higher elevations the pressure is less and the air consequently expands. Such expansion is usually approximately adiabatic in character and consequently air cools as it rises. Conversely, air which descends from higher elevations becomes warmer as it sinks. Air rising will cool

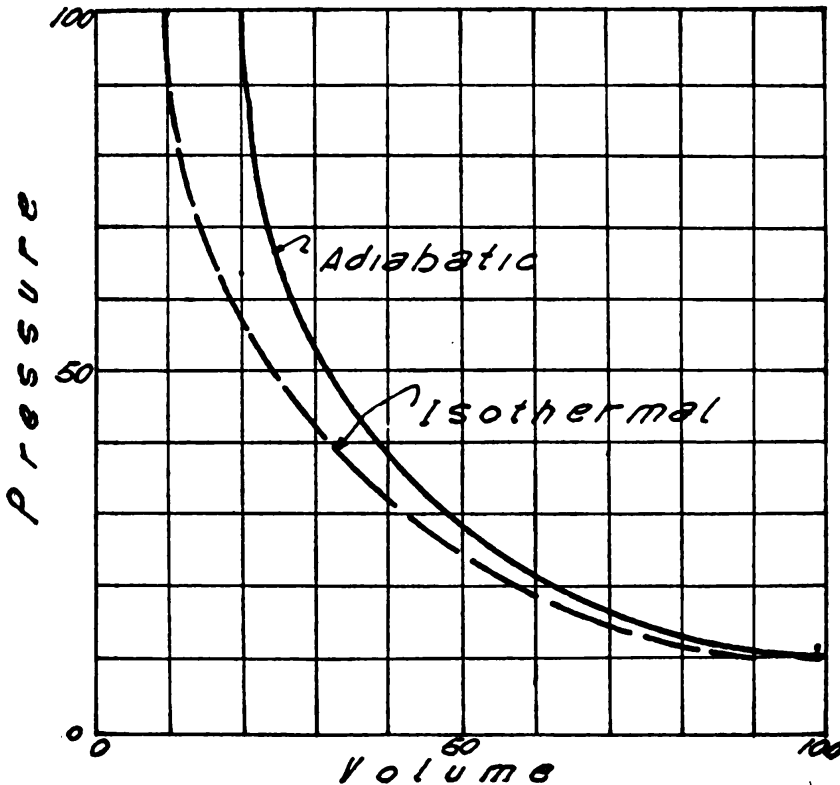


FIGURE 52.—Difference between adiabatic and isothermal compression of a gas.

approximately 3° C. for every 1,000 feet. This partially accounts for the fact that pilots find air at high elevations colder than at the ground. Such cooling is very pronounced and is usually sufficient to cause the water vapor in the air to condense and form clouds with a lift of the air of only 1,000 or 2,000 feet. The formation of clouds and precipitation in the atmosphere is almost always a result of this condensation. In storms some of the air is forced to rise and expand adiabatically. Clouds form in this air as a result of the cooling.

QUESTIONS AND PROBLEMS

1. What is an adiabatic process?
2. What is an isothermal process?

¹ γ is the Greek letter *gamma* and is universally used to designate this exponent.

3. If a paper bag containing 50 cubic inches of air is cooled from 100° C. to 0° C., what is the final volume?

4. If the above bag at original conditions is compressed with the hands until a gage reads three pounds per square inch, what is the new volume?

5. If the same bag has a capacity of 50 cubic inches, and 10 more cubic inches are forced in from outside, what is the final pressure as would be read by a gage?

6. If 20 liters of air at 10° C. and atmospheric pressure are first raised to a temperature of 50° C. and expanded isothermally to twice the former volume, what is the final total pressure? What would be the gage pressure?

7. In the adiabatic equation:

$$P_1 (V_1)^\gamma = P_2 (V_2)^\gamma$$

assume that the value of γ for a certain gas is 2. What will be the pressure if 10 cubic centimeters of this gas is adiabatically expanded to 14 cubic centimeters?

8. If the original temperature in example 7 were 27° C., what was the final temperature?

9. Very dry air is blowing up over a mountain range 10,000 feet high. A weather station on the windward side at an elevation of 5,000 feet reports a temperature of 0° C. What would be the temperature at the top of the ridge? At a station on the other side at sea level?

10. From the kinetic theory of gases it can be shown that the number of collisions per second on a unit area of surface is directly proportional to the velocity of the molecules. The kinetic energy of the molecules is directly proportional to the temperature of the gas. Show that the pressure of a gas is directly proportional to the absolute temperature if the volume is held constant.

SECTION XII

MOISTURE

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86. Matter in three states.—There are three states of matter: gas, liquid, and solid. In the preceding chapters these three states have been mentioned separately, but transformation of matter from

one state to another was not considered. Most inorganic substances in one state can be made to exist in the other states under proper conditions of temperature and pressure. Mercury is ordinarily liquid under normal conditions. Yet it freezes at -39° and boils at 360° C. Alcohol boils to vapor at 76° C. and freezes at -117° C. Also substances which are ordinarily solid can be melted to liquid. At sufficiently high temperatures, solids may even be vaporized. Gases under the proper conditions of temperature and pressure can be liquified and solidified. The air we live in can be made into liquid, and even into a solid. In general, then, most substances can be made to exist in any of the three states by proper regulation of pressure and temperature.

87. Three states of water.—Water may exist in the atmosphere in any of its three states; gas, liquid, and solid.

a. Gas.—Gaseous water is found mixed with the air in the form of water vapor. This water vapor, or moisture, in the atmosphere is picked up by evaporation as the air moves over water sources such as oceans, rivers, and lakes. The amount of moisture in the air is variable, depending upon the character of the earth's surface over which the air has moved.

b. Liquid.—Liquid water in the atmosphere is found in the form of clouds and rain, forming by condensation of water vapor. Condensation is the transformation from the gaseous to the liquid state.

c. Solid.—The solid form of water (ice) is found in the atmosphere in the form of ice clouds, snow, hail, etc. Ice may be found as a transformation either from the liquid state (freezing) or directly from the gaseous state (sublimation).

88. Transformation between the three states.—By increasing the temperature it is possible to melt ice into liquid water, or evaporate liquid water to water vapor; conversely, by lowering the temperature it is possible to condense water vapor to liquid water, or freeze liquid water into ice. What are these processes, especially with respect to temperature and energy? Suppose we have 1 gram of ice at -5° C., a thermometer to measure the temperature, and a heat source whose output (in calories) can be accurately measured.

a. Raising the temperature of the ice.—The heat source is applied and the temperature is raised from -5° C. to 0° C. Two and one-half calories are required to warm the ice from -5° C. to 0° C., or 0.5 calories for each degree centigrade rise in temperature. The specific heat of the ice, then, is .5 calories per gram per degree C. If the ice is cooled from 0° C. to -5° C., $2\frac{1}{2}$ calories are given off. To increase the temperature of a substance is to add energy to it; to cool a substance is to remove energy from it.

b. Change of state from solid to liquid.—The heat source is again applied, and ice at 0°C . melts to liquid water at 0°C . The melting of the ice takes 80 calories. As the temperature does not rise during this process, the 80 calories of heat are required for the change of state alone. Conversely, when 1 gram of water freezes to ice, 80 calories are given off. This 80 calories of energy emitted by freezing or absorbed by melting is called the *latent heat of fusion*. Latent means hidden; 1 gram of water at 0°C . has 80 calories that will be released when the water is frozen.

c. Raising the temperature of water.—The heat source is again applied, and the temperature of the water is raised from 0°C . to 100°C . Raising the temperature 100°C . requires 100 calories. If a temperature change for water is to be accomplished, calories (or energy) must be added to or taken from the water. The change in temperature is a direct change in energy. The specific heat of water (which is 1.0) is higher than that of most other substances. For this reason, oceans and lakes change temperature more slowly than adjacent land masses. From night to day the temperature of an ocean surface seldom changes more than 1 or 2 degrees.

d. Change of state, liquid to gas.—The heat is again applied and the liquid water at 100°C . is changed to water vapor at 100°C . This evaporation requires 540 calories. Since the temperature does not rise during this process, the 540 calories are required for the change of state. Conversely, when 1 gram of water vapor is condensed to liquid water, 540 calories are given off. This energy, 540 calories, required for this change of state, is called the *latent heat of vaporization or condensation*. There are many examples of condensation and evaporation in the atmosphere. The air picks up its moisture from the evaporating lakes, oceans, and rivers. This moisture is then mixed through the lower atmosphere by turbulence. Warm air can hold more moisture than cold air, but any air can be cooled to a temperature where the moisture or water vapor in that air will condense. This temperature is known as the dew point. In the atmosphere warm, moist air is lifted up over mountains or colder air masses, or is driven upward as a result of the sun's having heated the surface of the earth. As this air is lifted, it cools adiabatically and condensation will occur when the temperature reaches the dew point. Condensation will produce clouds and may even produce precipitation. Dew forms on the ground at night, because the earth's surface cools and reaches the condensation temperature, the dew point. Frost forms the same way except that the air is below the freezing temperature so that the water vapor is frozen directly to ice, or frost.

e. Explanation of boiling.—In the normal vaporization of water, the vapor above the surface will exert a pressure which depends upon the temperature. At low temperatures this pressure is small; but at a temperature of 100°C . the vapor pressure will be 14.7 pounds per square inch, equal to standard atmospheric pressure. At a temperature of 100°C . bubbles of pure water vapor can form within the fluid against the atmospheric pressure without. When bubbles of vapor form in this way and rise to the surface, we have the familiar process

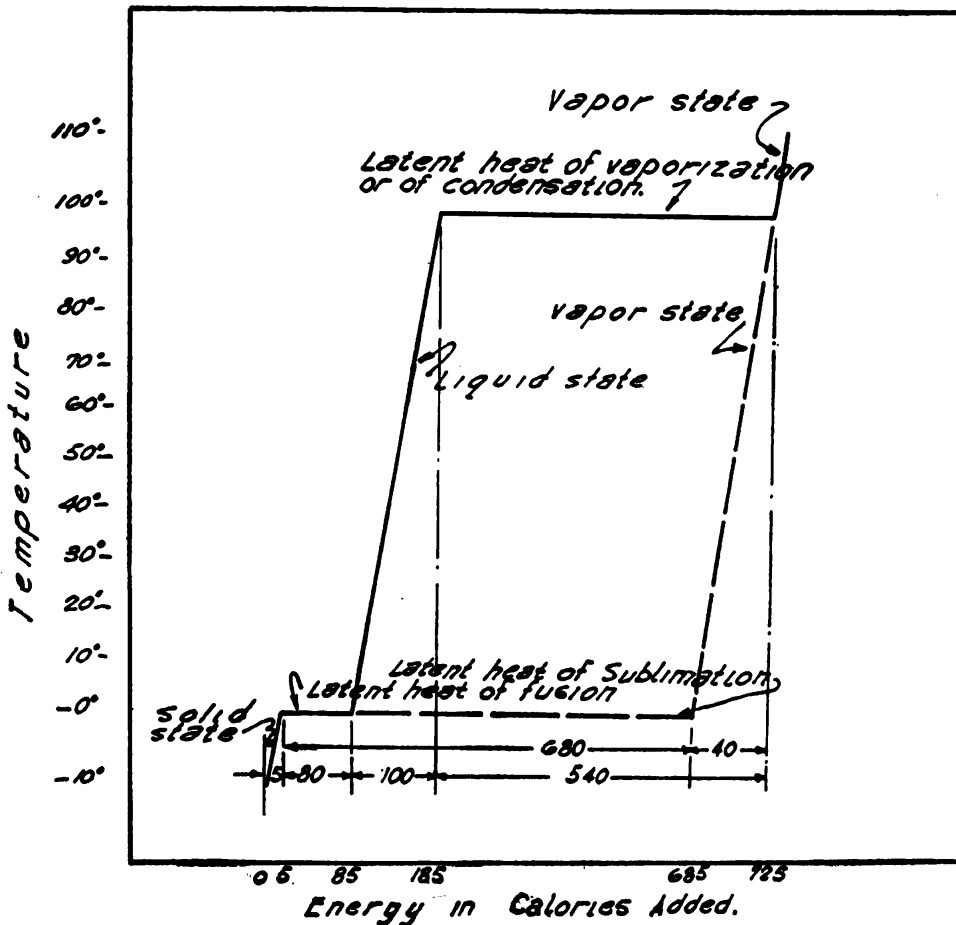


FIGURE 53.—Energy diagram for change in state of water.

of boiling. At high altitudes, where the atmospheric pressure is reduced, boiling can take place at lower temperatures because less vapor pressure is required to form bubbles.

f. Raising the temperature of water vapor.—The heat is again applied and the temperature of the water vapor is changed from 100°C . to 110°C . Raising the temperature 10°C . requires 4 calories of heat; consequently, the specific heat of water vapor is 0.4.

g. Energy diagram.—Figure 53 is a diagram showing the energy relationships in changes of temperature and changes in state of water.

h. Sublimation.—Certain substances in the solid state pass directly into the gaseous state, or conversely, gases may pass directly to the solid state. This process is known as sublimation. Dry ice is a good example. Solid carbon dioxide goes directly to CO_2 gas without ever liquefying. Iodine and ice will also readily sublime. When ice at 0°C . sublimates to water vapor, 680 calories per gram are absorbed. The eighty calories which would ordinarily be needed to melt the ice and the 600 calories which would be needed to boil the water at 0°C . are added together to equal the amount needed to sublime the ice to vapor. When the vapor sublimates to ice, 680 calories are given off. In the atmosphere the sublimation process plays an important part in producing rain, as will be explained in the next section.

89. Supercooled water.—It is possible under certain conditions to cool water to temperatures below 0°C . without freezing it into ice. Water in this state is called supercooled. If such water comes into contact with even a very small ice crystal, or is violently disturbed, freezing will take place rapidly, a sufficient portion of the water freezing to raise the temperature to 0°C . For instance, water at -5°C . requires 5 calories per gram to bring the temperature to 0°C ., and these 5 calories will be obtained from the latent heat of fusion of $5/80$ or $1/16$ of this water, which will be almost instantly frozen. Icing of aircraft occurs when the supercooled droplets in the atmosphere freeze on account of the violent disturbance produced by impact with the plane.

PROBLEMS

1. What would be the final temperature of a mixture of 1 liter of water at 20°C . and $\frac{3}{4}$ of a liter of water at 45°C .?
2. What would be the final temperature of a mixture of 100 grams of ice at -12°C . and 60 grams of water at 25°C .?
3. If 2 grams of superheated water vapor were passed into a 4-liter bucket of water at 20°C ., how warm would the water get if all the vapor were absorbed by the water and the vapor was originally at 120°C .?
4. Suppose that into a calorimeter containing 100 liters of water at 40°C . were dumped 5 kilograms of ice at 0°C . and 2 liters of water at 0°C . What would be the final temperature of the mixture?
5. How much ice at 0°C . would be required to lower the temperature of 100 grams of water at 35°C . to 10°C .?
6. Assume that the cold water in a shower is 15°C . and that the hot water is 85°C . Suppose you wanted to take a shower at 40°C . What would be the ratio of hot to cold water flowing into the shower nozzle?

7. Give to the nearest degree the final temperature of the following mixture: 50 grams of ice at 0°C. , 30 grams of water at 15°C. , and 3.2 grams of water vapor at 130°C.

8. An airplane flies through a supercooled cloud at -2°C. and picks up ice by impact with the water droplets. What percentage of each drop will have to freeze in order to bring the ice and water to 0°C. , which is the only temperature at which water and ice can remain in equilibrium?

9. An airplane flies through a cloud at -10°C. , and picks up ice on impact. What percentage of each drop will freeze in bringing the water and ice to equilibrium at 0°C. ?

10. In problem 9 how much of the remaining water at 0°C. must evaporate in order to freeze the rest of the water?

SECTION XIII

WATER IN THE ATMOSPHERE

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90. Physical states of water in the atmosphere.—Water is found in all three of its physical states in the atmosphere. As discussed in section XII, these three states are solid, liquid, and gas. At all levels at which tests can be made, water vapor may be found in any sample of air. The amount may vary considerably, but some is always present. Clouds and precipitation may be composed of either ice or liquid water, depending on their elevation, temperature, and history. Ice clouds usually exist only at the very high levels of 15,000 feet or more, but in very cold weather may occasionally be found close to the surface of the earth. Clouds with temperatures of 0°C. or higher are always water clouds. Both types of clouds are composed of extremely fine droplets of liquid water or particles of ice which because of their minute size remain suspended in the air.

91. Water vapor in the atmosphere.—*a.* Water vapor is a gas which in most respects acts very much like other gases. As long as its concentration does not exceed certain limits, it obeys the normal gas laws. When mixed with air it is normally unnoticeable, being colorless, odorless, and tasteless. Its density at a given temperature and pressure is only $\frac{1}{800}$ that of air. Being colorless, it is invisible because it contains no particles which can reflect light. Steam jets

are visible because of tiny particles of liquid water which have condensed from the vapor state.

b. When dry air passes over a water surface, a process called evaporation takes place wherein water leaves the surface and becomes mixed as a gas within the air. The reverse process of condensation takes place when air which is moist (that is, it contains a large amount of water vapor) comes into contact with a cold surface and water vapor leaves the air and deposits as liquid water or dew on the surface. In the free atmosphere, condensation takes place by the formation of small droplets on nuclei such as particles of sulfur trioxide or salt. When there are a large number of these drops in the air, this air is called a cloud or fog.

c. In any mixture of gases it may be imagined that the total pressure exerted by the mixture is the sum of partial pressures exerted by each individual component of the mixture. Each gas exerts a pressure which depends only on its concentration and its temperature, and is independent of the pressures exerted by any other gases mixed with it. In any such mixture the pressures exerted by each component will be in proportion to the number of molecules of each gas present. For instance, if 2 percent of the molecules in a sample of air are water molecules and the total pressure is 1,000 millibars, then the pressure exerted by the water vapor alone will be 20 millibars. This partial pressure exerted by water vapor in the air is called the vapor pressure.

d. Figure 54 shows a laboratory apparatus with which an experiment is performed. It is a form of manometer, or pressure measuring device, arranged to measure the pressure exerted by the vapor above a water surface at various temperatures. On the right-hand side of the U tube there is some liquid water with space above for vapor. On the upper left-hand side is a vacuum, and a mercury column separates the two sides. All air has been removed from the entire apparatus. The water may be heated or cooled to any desired temperature, which may be read on the thermometer. The pressure exerted by the vapor at any time will be indicated by the difference in height between the left-hand and right-hand mercury columns.

e. A plot of the pressure exerted at any temperature is shown on the graph in figure 55. The water is first frozen to ice, and at a temperature well below freezing the experiment is begun. The temperature is slowly raised and the pressure for each temperature is plotted on the graph. The result will be the solid line *AOB* on figure 55. Had the experiment been reversed (that is, had it been begun at a high temperature instead of a low one), the result would be the same except perhaps in the range of temperatures below freezing. Water may be

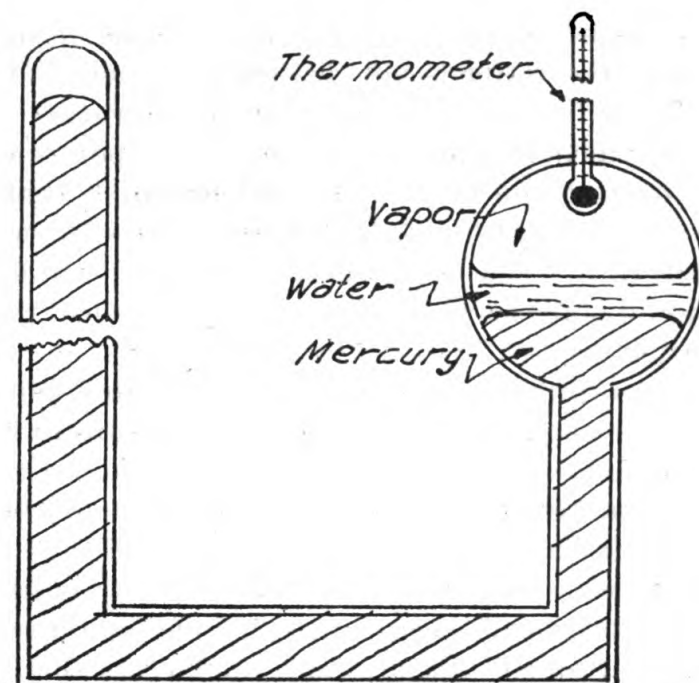


FIGURE 54.—Schematic diagram of apparatus for determining saturation vapor pressure of water at any temperature.

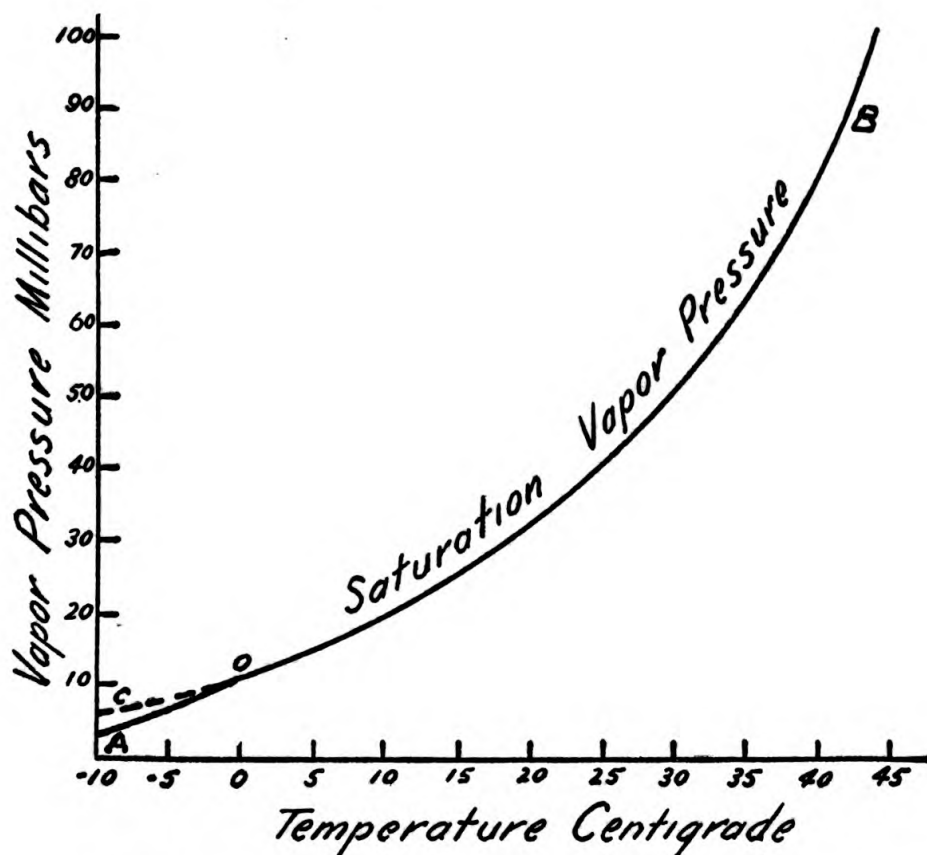


FIGURE 55.—Saturation vapor pressure of water at moderate temperatures.

cooled to temperatures below 0° C. without freezing if the container is very clean and the water is not disturbed. Such liquid water at temperatures below freezing is called supercooled water. Had supercooling been obtained in this experiment the vapor pressure curve would be the dashed line *OC*. It should be noted that the vapor pressure over ice is always less than over supercooled water at the same temperature. When ice vaporizes directly without passing through the liquid state or when vapor solidifies as ice, the process is called sublimation.

f. As the temperature is raised, water is evaporated (sublimed from ice) into the vapor chamber in order for the pressure to rise. When the temperature is lowered, the vapor recondenses and the pressures drop. For any one temperature there is a maximum pressure which vapor may exert, and any attempt to exceed this will result in condensation. If liquid water is present and the pressure is less than this maximum, evaporation will occur until this maximum or saturation vapor pressure is attained. Saturation is defined as that state where the vapor pressure is the maximum possible for that temperature. This saturation vapor pressure always increases with temperature, increasing more rapidly at high temperatures than at low temperatures. In the atmosphere the rules just stated still hold, the saturation partial pressures of water vapor following the same curves as in figure 55. The presence of the air has almost no effect on the above relation if the partial pressure of the vapor alone is considered.

92. Changes of state of water in the atmosphere.—*a.* Ordinarily the air in the atmosphere contains insufficient water vapor to cause saturation. This is known as “dry” air, but “dry” in this sense does not mean that there is no water vapor in the air. If for any reason this air becomes saturated, it is then spoken of as “wet.” There are two fundamental ways in which air may become saturated. One is by evaporation; that is, the air picks up water vapor until it can hold no more. The other is by cooling; that is, as the temperature of the air is reduced, its ability to hold water vapor is reduced, the saturation point being reached when the temperature drops to where the amount of water vapor necessary to cause saturation is the amount originally present. In this latter process no water vapor is actually added to the atmosphere. Either process or a combination of the two may cause atmospheric air to become saturated, cooling usually being the direct cause. Evaporation is, of course, a very important process in weather, but it seldom alone produces saturation.

b. Saturation of the atmosphere is a very important phenomenon and is the direct cause of all precipitation such as rain, snow, or

drizzle. Saturation first forms clouds which with further cooling may give precipitation. The cooling necessary for saturation may be caused in several different ways. Lifted air will expand adiabatically and be cooled thereby. Warm air may be cooled by passing over colder ground. The first condition will produce clouds and perhaps rain, and the second condition may produce fog. If the air is moist and warm, condensation will form small water droplets; but if it is dry and cold so that the saturation temperature is below freezing, sublimation will occur and ice clouds or ice fog will form. If a cloud is already present and the temperature is raised, the water or ice particles will evaporate and the cloud will disappear because at higher temperatures the air can hold more water vapor.

93. Expressions for the amount of water vapor in the air.—

As shown above, for any temperature there is a limit to the amount of water vapor that may be present in the air. Usually the amount is less than this maximum, and it is often important to know the amount which is present in order to predict certain weather phenomena. In the following paragraphs several methods for expressing quantitatively the air's water vapor content are explained:

a. Vapor pressure.—Vapor pressure has already been defined as the partial pressure exerted by water vapor in the air. If the vapor pressure and temperature are known it is a simple matter to use the gas laws to find the amount of water vapor present in any known volume or in any sample of air.

b. Dew point.—The dew point is defined as that temperature to which any sample of air must be cooled (keeping the total pressure constant) in order to be brought to the saturation point. Because of the unique saturation vapor pressure for each temperature, it may be seen that air which will become saturated at a definite temperature will have a unique amount of water vapor present at the original conditions as well as at the saturation point. Dew point is a very useful expression because it quickly shows the amount of cooling necessary before condensation begins.

c. Specific humidity.—Specific humidity may be defined as the number of grams of water vapor present in 1 kilogram of air. Any units may be used if the specific humidity is considered as the ratio of the weight of water vapor in any sample to the weight of the total sample, multiplied by 1,000. If there is no condensation or evaporation, the specific humidity of any sample of air will remain constant, even though the pressure, temperature, or volume of the sample changes.

d. Relative humidity.—Relative humidity is the ratio, usually expressed in percent, of the actual amount of water vapor present to that which the air could hold if the air were saturated at that temperature. If the vapor pressure of some sample of air is 2 millibars and an inspection of the graph in figure 55 shows that at that temperature the saturation vapor pressure is 4 millibars, then the relative humidity is 50 percent.

e. Absolute humidity.—Absolute humidity is defined as the weight of water vapor present in a given volume of air; for instance, it may be expressed in grams of water vapor per cubic meter of air. It is not a conservative property like specific humidity, as there will be a change in its value when there is expansion or compression.

94. Methods of measuring humidity.—There have been devised no really accurate indicating meters for humidity, but there are in use several fairly convenient devices which give results sufficiently accurate for most purposes. Three of these devices are described in the paragraphs below.

a. Wet and dry bulb thermometers.—(1) Two thermometers are used in this method; one is a normal thermometer for measuring the temperature of the air, and the other is equipped with a moistened wick around the bulb. With good air circulation around the thermometers the wet bulb will normally cool to a temperature below that of the dry bulb. Because of the energy required for evaporation, there is a cooling effect which depends upon the rate of evaporation. If the air is nearly saturated, the rate of evaporation is small, and the wet bulb will have a temperature close to that of the dry bulb. In very dry air (that is, air with low relative humidity) there is rapid evaporation, and the wet bulb may be several degrees cooler than the dry bulb. A set of tables must be used to convert these two temperatures into an expression for humidity.

(2) Several different instruments have been devised using the above principle, but the one in most common use is the sling psychrometer. The device consists of the two thermometers attached rigidly together and the combination attached at the top end to a handle arranged so that the thermometers may be whirled vigorously about. The whirling provides the ventilation necessary to give accurate wet bulb readings. In use, the wick is wet with pure water and the device is whirled about. After the wet bulb has dropped in temperature as far as it will, the two readings are taken and the table is consulted to determine the dew point, relative humidity, or vapor pressure. More complicated devices on the same principle may use a fan to provide the necessary ventilation. A drawing of the sling psychrometer is shown in figure 56.

b. Hair hygrometer.—A human hair, after it has been cleaned of its natural oils, has the property of absorbing water from the air and thereby increasing its length. The amount of water absorbed and the

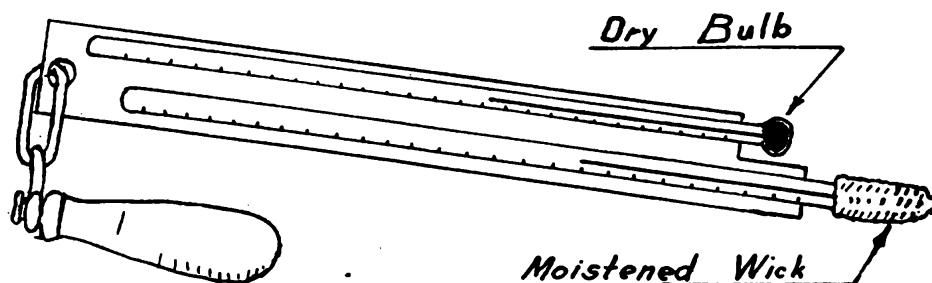


FIGURE 56.—Sling psychrometer.

degree of lengthening depend upon the relative humidity. The amount of this lengthening is not very great, but mechanical linkages may be used for magnification of the movement. A needle may be used to indicate the relative humidity on a scale. A drawing showing an arrangement for an indicating hair hygrometer is shown in figure 57.

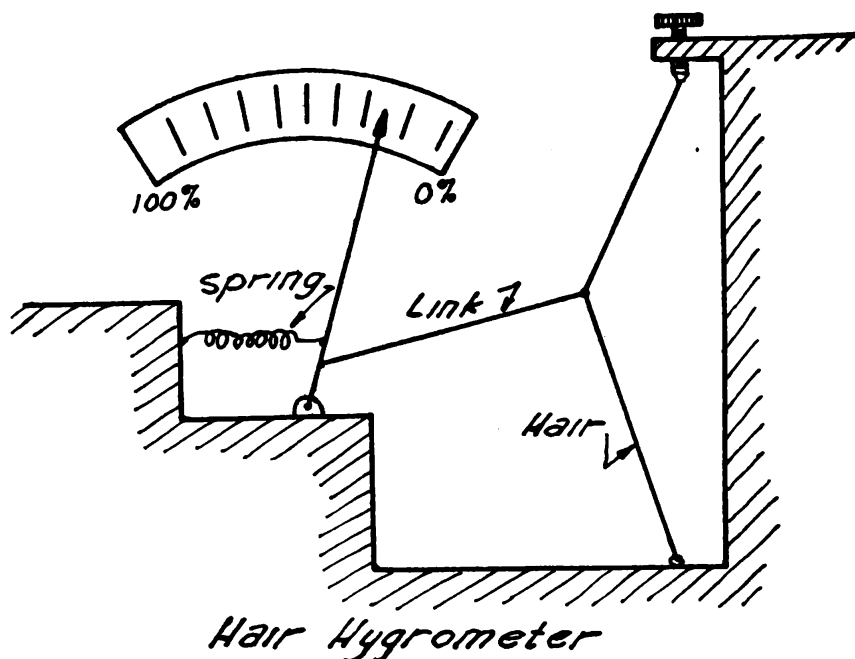


FIGURE 57.—Schematic diagram of magnification linkage for a hair hygrometer.

c. Dew point indicator.—If air is cooled to the dew point, condensation takes place. If a cold surface is at the dew point temperature, water will condense on the surface as dew. An ice pitcher becomes wet on the outside for this reason. The instrument used for indicating the dew point consists of a shiny, metallic surface which may be cooled to any desired temperature. The temperature at which the

surface first becomes fogged with dew is the dew point. In practice the device is not convenient to use because of the difficulties in determining just when the dew first forms and because of the difficulties in keeping an accurate knowledge and control of the temperature.

95. Hydrometeors.—Water products, either falling or in suspension in the atmosphere, are termed hydrometeors. Clouds and their precipitation products come under such classification and will be discussed in this section.

a. Clouds.—The three major criteria for the classification of clouds are composition, structure, and elevation. With respect to elevation, clouds may be either high, medium, or low. High clouds have elevations of their bases above 20,000 feet; medium clouds, between 6,500 and 20,000 feet; and low clouds, below 6,500 feet. With respect to composition, clouds may be made up of tiny particles of ice, liquid water, or both. With respect to structure, clouds may be classified as stratiform or cumuliform. Stratiform clouds are of a sheetlike structure formed in layers of large horizontal extent. Cumuliform clouds are those which seem to build upward in isolated patches, usually with a puffy, cauliflower appearance. They may vary in size from a small patch in the sky to the towering, mountainous mass associated with thunderstorms. Stratiform clouds are formed in air whose movements are almost entirely horizontal, while cumuliform clouds are formed by irregular, up-and-down air currents. Listed below are the major cloud types together with their classifications and a short description of each:

(1) Cirrus clouds are stratiform in structure, have a high elevation, and are composed of ice crystals. Cirrus forms in thin, wispy streaks across the sky through which the sun or moon may be seen. They are the highest of all clouds normally found.

(2) Cirrostratus is a high, ice, stratiform cloud. It forms in a thin veil as a large sheet covering all or a large portion of the sky. It does not blot out the sun, moon, or bright stars. Its presence often causes the halo sometimes seen around the sun or moon.

(3) Cirrocumulus is a high, ice, cumuliform cloud. It forms in small patches of thin cloud, usually in some regular pattern like the scales of a fish.

(4) Altostratus is a medium height, stratiform cloud of either ice or water composition. It forms as a fibrous veil across the sky and may or may not hide the sun or moon. It may cause a precipitation of light rain or snow.

(5) Altocumulus is a medium height, cumuliform cloud of either ice or water composition. It forms a layer of flattened globular masses

often arranged in some regular pattern across the sky. It may cause a precipitation of light rain or snow. A mackerel sky is caused by altocumulus.

(6) Nimbostratus is a low, stratiform cloud composed of either ice or ice and water. It is a thick, dark, ragged cloud which gives a continuous precipitation of either rain or snow, perhaps heavy.

(7) Stratocumulus is a low elevation, cumuliform, water cloud. It forms in a layer of globular masses or rolls across the sky with limited vertical development but often packed very closely together. It ordinarily gives no precipitation.

(8) Stratus is a low, stratiform, water cloud. It is usually not very thick and has a light gray color. Usually it is a local cloud which forms at night and disappears in the day. The precipitation, if any, will be a drizzle.

(9) Cumulus is a low elevation, cumuliform, water cloud. It forms in scattered dense white masses with a cauliflower appearance and flat, horizontal bases. It usually forms in the daytime as a result of convective currents set up by the sun's heating. When cumulus clouds are of large size and grow rapidly they may develop into cumulo-nimbus.

(10) Cumulo-nimbus is a cumuliform cloud with immense vertical development. The base is of low elevation, but the top may extend to 20,000 or 30,000 feet. The lower portion of the cloud will be composed of water droplets, but the upper portion will contain ice crystals. The upper portion of the cloud may spread out to form a characteristic anvil shape. All such clouds produce showers, but in extreme cases they may result in thunderstorms with hail and torrential rain.

(11) Fog is any cloud which touches the ground. Usually it is of a local and temporary character, forming at night and disappearing in the daytime. Fog is most commonly caused by nighttime cooling of surface air to the temperature where condensation takes place. It is a stratiform cloud usually composed of water particles, though ice fogs occasionally form.

b. Precipitation.—When air containing water vapor is cooled to a temperature below the dew point, the first condensation products are clouds. Ordinarily a large amount of water may condense in this way without the tiny cloud droplets becoming of sufficient size to fall as precipitation. The process by which precipitation is formed is not too well understood, but it is generally conceded that particles large enough to fall as rain will not ordinarily be formed unless the upper levels of the cloud are at temperatures below freezing. An inspection of the vapor pressure temperature curve of figure 55 will show that

the vapor pressure of ice is less than that of supercooled water at the same temperature. As condensation ordinarily occurs in air which is being lifted, some liquid water will usually be found at levels where the temperature is below 0°C. , together with newly formed ice particles. Because of the difference in vapor pressure between these two kinds of water, it is thought that there is a rapid transfer of water from one to the other by evaporation of the supercooled water and sublimation onto the ice particles. In this way the ice particles could grow rapidly in size and soon become large enough to fall downward. After the first large particles are formed, many changes may take place, and the conditions of the air through which the particles must fall will determine the kind of precipitation which will finally reach the earth. Several of the different forms which precipitation may take are described in the next few paragraphs, together with a short description of the processes required for their formation:

(1) Rain is simply a fall of large drops of liquid water. The original ice particle melts in warmer air below and may increase in size by picking up more water in the clouds below. Rain drops have a diameter greater than $\frac{1}{60}$ of an inch.

(2) Drizzle is a fall of very small particles of liquid water. The particles must have a diameter of less than $\frac{1}{60}$ of an inch and will fall with velocities of less than 10 feet per second. Drizzle does not require freezing temperatures for its formation and is usually the only type of rain which can fall from water clouds.

(3) Freezing rain and freezing drizzle is simply rain or drizzle which falls through a layer of cold air so that the particles become supercooled. Freezing rain or drizzle causes glazing because it freezes upon impact with objects in the open.

(4) Snow is a fall of white or translucent ice crystals. It is formed by direct sublimation from water vapor.

(5) Sleet is a fall of grains or pellets of ice. It is formed by the freezing of rain when it falls through a cold layer of air below.

(6) Hail is a fall of ice balls or stones of a size which varies from $\frac{1}{8}$ inch to 2 inches or more in diameter. Hail may be either transparent ice or layers of opaque snow and ice. Hail is formed almost exclusively in thunderstorms and requires violent upward currents of air for its formation. It is very hazardous to aircraft and is one of many reasons why thunderstorms should be strictly avoided by pilots.

(7) Snow pellets are falling grains of a snowlike structure, crisp but easily compressible; they rebound upon striking the ground. Snow pellets form in upward air currents and are often found with showers.

TABLE V.—*Saturation vapor pressures and saturation specific humidities at various temperatures*

Temperature		Saturation vapor pressure (millibars)	Saturation specific humidities (grams per kilogram)
Centigrade	Fahrenheit		
— 20	— 4	1. 27	0. 77
— 10	14	2. 86	1. 76
— 5	23•	4. 21	2. 59
0	32	6. 11	3. 77
5	41	8. 27	5. 36
10	50	12. 28	7. 58
15	59	17. 05	10. 50
20	68	23. 38	14. 40
25	77	31. 68	19. 50
30	86	42. 45	26. 10
35	95	56. 23	34. 60
40	104	74. 10	45. 60
45	113	95. 84	59. 10

At temperatures below freezing, these values apply to supercooled water. For ice, the values will be slightly lower.

QUESTIONS AND PROBLEMS

1. Why does warm, moist air cause more discomfort than warm, dry air?

2. If air with a relative humidity of 50 percent is expanded adiabatically, will the following quantities increase or decrease? (a) vapor pressure, (b) relative humidity, (c) specific humidity, (d) absolute humidity, (e) dew point.

3. If air in the free atmosphere at 25° C. has a dew point of 20° C., describe what will occur if the air is slowly cooled to —10° C.

4. If laundry is hung out to dry at temperatures below freezing, what process is responsible for the disappearance of the water?

5. At a temperature of —5° C., which will transform into vapor more quickly, supercooled water or ice? Assume similar conditions for each.

6. If air in a small chamber has a temperature of 25° C. and a dew point of 15° C., what is the approximate vapor pressure?

7. If air has a specific humidity of 5.25 gr per kg, at what temperature would the relative humidity be 50 percent?

8. If air has a dew point of 50° F., what will be the relative humidity if the air is at a temperature of 104° F., 77° F., 68° F., and 50° F.?

9. If air has a temperature of 20° C. and the relative humidity is 52 percent, approximately how much water will condense if the temperature is reduced to 0° C.?

10. A kilogram of air is saturated with water at normal pressure and then expanded to twice its former volume. If during this process the temperature is reduced from 25° C. to 0° C., how many grams of water will be condensed?

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